A PRACTICAL TREATISE

ON

LOCOMOTIVE ENGINES.

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LOCOMOTIVE ENGINES;

A WORK INTENDED

TO SHOW THE CONSTRUCTION, THE MODE OF ACTING, AND THE USE OF THOSE ENGINES FOR CONVEYING HEAVY LOADS ON RAILWAYS; TO GIVE THE MEANS OF ASCERTAINING, ON AN INSPECTION OF THE MACHINE, THE VELOCITY WITH WHICH IT WILL DRAW A GIVEN LOAD, AND THE EFFECTS IT WILL PRODUCE UNDER VARIOUS CIRCUMSTANCES; TO DETERMINE THE QUANTITY OF FUEL AND WATER IT WILL REQUIRE; TO FIX THE PROPORTIONS IT OUGHT TO HAVE, IN ORDER TO ANSWER ANY INTENDED PURPOSE; ETC.

FOUNDED ON

A GREAT MANY NEW EXPERIMENTS,

MADE ON A LARGE SCALE, IN A DAILY PRACTICE, ON THE LIVERPOOL AND MANCHESTER, AND OTHER RAILWAYS, WITH MANY DIFFERENT ENGINES, AND CONSIDERABLE TRAINS OF CARRIAGES.

TO WHICH IS ADDED,

AN APPENDIX;

SHOWING THE EXPENSE OF CONVEYING GOODS, BY LOCOMOTIVE ENGINES, ON RAILROADS.

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BY THE COMTE F. M. G. DE PAMBOUR,

FORMERLY A STUDENT OF THE ECOLE POLYTECHNIQUE, LATE OF THE ROYAL ARTILLERY, ON THE STAFF IN THE FRENCH SERVICE, KNIGHT OF THE ROYAL ORDER OF THE LEGION D'HONNEUR, OF THE ROYAL ACADEMY OF SCIENCES OF BERLIN, ETC.

DURING A RESIDENCE IN ENGLAND FOR SCIENTIFIC PURPOSES.

A Second Edition,

INCREASED BY A GREAT MANY NEW EXPERIMENTS AND RESEARCHES.

LONDON: JOHN WEALE.
1840.

LONDON:
W. HUGHES, KING'S HEAD COURT, GOUGH SQUARE.

INTRODUCTION

TO THE FIRST EDITION.

THERE exists no special work on locomotive engines. Two writers, Wood and Tredgold,[1] have indeed, in England, slightly touched upon that matter, but only in a subordinate manner, in treatises on railways; and, besides, they both wrote at a time when the art was scarcely beyond its birth. Consequently their ideas, their calculations, and even the experiments they describe, have hardly any relation to the facts which actually pass before our eyes, and can be of no use to such as wish to acquire a knowledge of these engines and their employ on railways.

Many questions had not even been entered into, others had been solved in a faulty manner. New researches on the subject became therefore indispensable. This work will, in consequence, be found completely different from

[1] 'A Practical Treatise on Railroads, and Interior Communication in general, by Nicholas Wood.' 1st edition, London, 1825; 2d edition, London, 1832.

'A Practical Treatise on Railroads and Carriages, by Thomas Tredgold.' London, 1825.

any thing that has been published hitherto. No facts will be quoted, but such as result from actual observation; no experiments related, but those made by the author himself, on a new plan, and with new aims; finally, no theory exposed, but such as is derived from those experiments.

If at first sight it appear astonishing that no theory of locomotive engines should exist, the surprise ceases on considering that the theory of the steam engine itself, taken in general, has not yet been explained. It was natural to suppose, that, respecting a machine at present in such universal use, and on a subject of such importance, every thing had been said, and every explanation given long ago. Far from this being the case, however, not even the mode of action of the steam in these engines has been elucidated. In the absence of such indispensable knowledge, all theoretical calculations were impossible. Suppositions were put in the place of facts. In consequence, we have seen very able mathematicians propose, on the motion of the piston in steam engines, analytical formulæ, which would certainly be exact, if all things went on in the engine as they suppose; but which not being founded on a true basis, fall naturally to the ground, in presence of facts. From this also results that, in practice, the proportions of the engines have only been determined by repeated trials, and that the art of constructing them has proceeded hitherto in the dark, and by imitation.

Locomotive engines being first of all steam engines, we cannot advance in the researches we undertake, without solving at the same time the question relating to steam engines in general. There is even a remarkable point to

be observed, which is, that of all sorts of steam engines, locomotive ones are those which, in their application, have to overcome the least complicated resistance, and the most susceptible of a rigorous appreciation. This circumstance renders them therefore more proper than any others, for furnishing an explanation of general facts common to all those machines. The theory once satisfactorily established in regard to locomotive engines, will, of course, apply equally to all sorts of steam engines, and more especially to those which, like locomotive ones, work at a high pressure.

We flatter ourselves, therefore, that our researches, although apparently confined to locomotive engines, may at the same time illustrate the principal points of the theory of steam engines in general.

However, in order to indicate clearly the design of this work, and to show in what it differs from those that have preceded it, we think proper to enter here into some particulars as to the points on which we have new researches to offer, either theoretical or experimental. It will be seen that those points embrace nearly the whole subject.

The pressure of the steam in the boiler had been, till now, considered as invariable in every engine. It was calculated once for all, and by approximation, according to the weight on the valve. A great number of observations will show, however, how much it varies during the motion of the engine, and how necessary it is to take that circumstance into consideration, and to make use of a more exact mode of determination, lest the calculation should be entirely founded on an erroneous basis.

The friction of the waggons was, until now, valued much too high. This error naturally rendered every calculation false, by misleading with regard to the true resistance overcome by the engines. A great number of experiments on waggons, alone or united in considerable trains, will have for their object to show the real value of the friction.

The resistance of locomotive engines was still an unsolved question. We have endeavoured to determine it by three different processes, which may serve to verify each other.

The additional friction created in the engine by the load it draws, had never yet been submitted to any investigation. We shall present numerous experiments on that subject.

The exact determination of the pressure of the steam in the cylinder, was necessary to explain the mode of action of locomotive engines, as well as that of steam engines in general, and to calculate the work they can perform in different circumstances. The erroneous ideas admitted in that respect, were the origin of all the faulty calculations, which experiment contradicted. We trust that the simple elucidation of that point will in a manner lay open the whole play of the engine.

The evaporating power of the engines was an element on which no experiment had yet been made, which was not even introduced in the calculations, and on which, however, definitively depends the effect these engines are able to produce. Experiments made on that subject, upon a great number of engines, will be found in this work.

An analytical equation, that might be adapted to solve

the general problem of locomotive engines, was entirely wanting; that is to say, an equation by which might be known *à priori*, either the effects resulting from the given proportions of an engine, or, *vice versâ*, the proportions that ought to be adopted, in order that predetermined effects in regard to load or speed may be obtained. The trials hitherto made to come to a solution of this question, being founded on a false principle, had produced formulæ in evident contradiction with facts. A rule had even been adopted, according to which the practical power of an engine was considered as equal to the third part only of its calculated or theoretical power; whereas, the whole applied power must evidently appear in the effect produced, and we shall see that it really does appear in it. This imaginary rule is a sufficient proof of the error of the calculations that were used, and could only lead to disappointments in practical applications. Engines were constructed, but the effect that they would produce was unknown. By the introduction of a new element of calculation, wrongly neglected until now, viz. the vaporizing power of the engines, it will be seen, that that question is solved in the most simple manner possible. From that equation, and simply by measures taken on the machine, the velocity and load of a locomotive engine may be immediately found, and *vice versâ*, the proportions which ought to be given to it, to make it answer any intended purpose. A great number of experiments, made in a daily practice, will show the accuracy of the formulæ. This is, at the same time, the theory of all high-pressure steam engines.

Several secondary dispositions of the mechanism of the

engines had not yet been studied. It will, however, be seen that they are apt to deprive the machine, in certain circumstances, of as much as a fourth part of its power. The effects of these dispositions, and in particular of that which is called the *lead of the slide*, will be submitted to calculation, and the results verified by special experiments.

The resistance proper to the curves of the railway deserved also to fix our attention. We shall endeavour to fix accurately the form of the wheels, and the disposition of the rails, by which that resistance may most effectually be remedied.

The consumption of fuel according to the load had not been determined in a satisfactory manner, and the rule proposed was contradicted by the experiment. This question will be established in a different manner, and the results confirmed by facts.

The researches on those points were made on twelve different engines, and numerous experiments were undertaken on each branch of the subject.

The method constantly followed consists in taking, first, the primary elements of the question from direct experiment; then making use of those elements to establish a calculation in conformity with theoretical principles; and, lastly, submitting the results to fresh and special experiments, in order to obtain their verification. For the further elucidation of the formulæ, they are each time carefully submitted to particular applications; and, finally, to extend the use of the work to persons who may wish to find the results without calculations, the formulæ are followed by *practical* Tables, suitable to the cases which occur the most frequently in practice.

It does not enter into the plan we have traced ourselves, to give an elaborate description of the engine, nor the measures of its different parts, except those necessary for the researches we undertake. Such considerations would lead us too far, and concern more particularly works on construction. In like manner, the figures of the Plates added to our work are only meant as illustrations of the text. They would be too imperfect for any other object.

The untrodden path in which we have been forced to enter, may have led us into some error. We by no means pretend to have produced a perfect work, and we claim indulgence for the mistakes which may have escaped us in so new a subject. Our chief aim was to be useful, while seeking a study congenial to our taste, and occupying the leisure of an inactive life. Early devoted to other pursuits, belonging to a family for several generations engaged in the military career, and the son of a General of Artillery, whose footsteps had naturally traced our direction, our studies would not have taken that turn, had we not been struck by the powerful effects of the moter we are going to describe, and by the important part it must necessarily act in modern civilisation. We thought our work would at least have this result, to call the public attention to the subject. We shall feel happy if we have succeeded in some of our researches; and happy also if others, in correcting our errors, shall at least elucidate the facts upon which we have called their attention.

All the experiments related in the work were made by *ourselves*, with all the care and attention they required. Some were made in company with engineers of known

talent and ability, as Mr. J. Locke, of the Grand-Junction Railway, and Mr. King, of the Liverpool Gas Works. We give them in all their details, with a view that every one may judge of their accuracy; and we mention the place and date of each experiment, in order to facilitate their verification by referring to the books, in which is registered the weight of each of the trains.

In regard to the facility we had of making these numerous experiments, we must say that, having applied to the heads of the most important concerns of the sort in England, we were permitted, without restriction, to penetrate into the workshops, to take every measure, to collect all the documents concerning the expenses, and, lastly, to make any experiment that appeared necessary to us.

It is with pleasure we acknowledge in the English character the liberality we have found in the whole course of our investigations.

To the friendship of Mr. Hardman Earle, one of the Directors of the Liverpool and Manchester Railway, we owe in particular our warmest thanks. His obligingness never abated. Possessing all the qualities of an enlightened mind, he liked taking a part in researches which appeared to him conducive to the progress of science; and he permitted us to use all the engines and waggons of the railway. The beauty of these engines, their number, which is not less than thirty, the care with which they are kept, and the immense trade on that line, which gives the facility, without interfering with the business of the railway, to select loads for experiments as considerable and as light as one wishes, make that place the only one, perhaps, in the world, where experiments on a great scale

may be made with the same precision as in general can only be obtained by a small apparatus. It is for that reason we preferred that railway to any other at present in activity, either in France or in England.

The same facilities were also offered us by the Directors of the Stockton and Darlington Railway. Interesting documents concerning the repairs and expenses of all sorts, incurred by that Company, were obligingly communicated to us. We owe that obligation to the liberal authorization of Mr. J. Pease, M.P., Chairman of the Company, and to the unremitting attentions of Mr. Robert B. Dockray.

We have studied the subject with all the interest, and, we might say, with all the enthusiasm it excited in us. In fact, what a subject for admiration is such a triumph of human intelligence! What an imposing sight is a locomotive engine, moving without effort, with a train of 40 or 50 loaded carriages, each weighing more than ten thousand pounds! What are henceforth the heaviest loads, with machines able to move such enormous weights? What are distances, with moters which daily travel 30 miles in an hour and a half? The ground disappears, in a manner, under your eyes; trees, houses, hills, are carried away from you with the rapidity of an arrow; and when you happen to cross another train travelling with the same velocity, it seems in one and the same moment to dawn, to approach, and to touch you; and scarcely have you seen it with dismay pass before your eyes, when already it is again become like a speck disappearing at the horizon.

On the other hand, how encouraging is the evident

prosperity of those fine establishments! How satisfactory it is to acquire the proof that the Liverpool and Manchester Railway produces 9 per cent. interest, and the Stockton and Darlington an equal profit! With what confidence must we not anticipate the future state of such undertakings, when we know that, besides the above-mentioned annual interest, the shares of the Liverpool Railway have risen, in four years,[2] from £100 to £210; and those of the Darlington Railway, in eight years, from £100 to £300? What may not society at large expect in future from this new industry, which will augment, tenfold, the capital and produce of the country, by the immense influence of speedy and economical conveyance!

It is then with the liveliest wish to see this new branch of industry diffused as it merits, that we have undertaken the work which we now present to the public.

[2] The first edition of this work appeared in French, in the beginning of 1835.

INTRODUCTION

TO THE SECOND EDITION.

The Introduction to the first edition, which is here reprinted such as it was published in 1835, exposes the plan we had proposed to ourselves in this work, and the facilities that were afforded us for studying the subject. But as a first essay necessarily falls short of what is to be desired, we have since devoted ourselves to new researches, to endeavour, as far as in us lies, to supply the deficiencies which at first we could only indicate.

This task we began in the month of August, 1836, as will be seen by the dates of the experiments which will be presented in the work. Unable, at the period of our first edition, to find a satisfactory means of separating, in our experiments, the resistance of the air against the trains, from the friction proper to the waggons, we were constrained to take account of that resistance at an average velocity of 12 to 15 miles per hour, leaving it united to the friction of the waggons, that is to say, giving a valuation of those two resistances together at that velocity. But recognising the want of a more precise determination of the special value of each of those two resistances, we

undertook, in the month of August, 1836, on the Liverpool and Manchester Railway, a series of experiments on the subject, and published the results of them, blended with other matters, in a series of papers printed in the *Comptes rendus* of the sittings of the Academy of Sciences of the French Institut of 1837. And indeed we were not a little surprised to find in 1839, in the proceedings of the British Association for the Promotion of Science, a long article by an English Professor, who, without noticing these ulterior researches, indulged himself with the satisfaction of pointing out to us an omission already published by ourselves, and remedied long since; and who, in fine, proposed a new valuation of the resistance of the trains, according to which, far from separating the resistance of the air from the friction of the waggons, he pretended on the contrary that the separation was impossible in the present state of science on the subject.

The experiments which we undertook at the same period on the Liverpool and Manchester Railway, comprise also several other researches, such as the pressure against the piston caused by the action of the blast-pipe, the vaporization of boilers in different circumstances of rest and of motion, the effects of a different proportion between the fire-box and the tubes, on the total vaporization of the engine, and on its consumption of fuel, &c. The results of the greater part of these experiments have been communicated separately to the Academy of Sciences, in the course of the years 1838, 1839, and 1840, and printed in the *Comptes rendus;* but they are now collected in this edition, and so arranged, as to complete as much as possible the data already offered on locomotive engines.

We could have wished all these researches to be quite conclusive; but we do not dissemble that many among them are as yet but very incomplete, that they require further study and more varied observations. Such, however, as they are, we yet think them capable of leading to useful results; and, at all events, they will have the advantage of pointing out the road to other experimenters on the same subjects. We shall be among the first to receive with eagerness the new lights which their labours may elicit.

The publication of another work, the subject of which appeared to us to be very important, the *Theory of the Steam Engine*, prevented us, till now, from bringing out the second edition of the *Treatise on Locomotive Engines*, though the first had long been out of print. The adoption, by a great number of authors and engineers,[1] of the theory and experimental determinations contained in the first edition, and the re-production of the work in England, in America, and in Germany, seem to us an ample reward for all the application and labour it has cost us. But as some authors, in rendering an account of our researches,

[1] In France, M. Navier, member of the *Institut;* in England, Professor Whewell, of the Royal Society of London, in the fifth edition of his *Treatise on Mechanics;* in Prussia, M. Crelle, of the Royal Society of Sciences of Berlin, &c., have adopted these researches; and in the third edition of his work on Railways, London, 1838, Mr. Nicholas Wood has inserted, in detail, not only all the experimental determinations of the *Treatise on Locomotive Engines*, but even the *theory* of that engine developed in the same work, acknowledging, in a slip expressly added at the head of that edition, the source from which he took that theory.

have given a mistaken analysis of them, or have drawn from them consequences which we cannot admit, we deem it necessary to enter into some details on this subject.

In the edition published in 1838, by Mr. Woolhouse, of Tredgold's work on the Steam Engine, page 186 of the Appendix, the editor, wishing to give a succinct analysis of our *Theory of the Steam Engine*, the same as will be found developed in Chapter XII. of this work, but specially applied to locomotive engines, says that our theory "may be briefly explained thus: if the evaporating power of the boiler be capable of supplying a greater quantity of steam, at the required pressure, than is consumed at the successive strokes of the piston, it is evident that the pressure of the steam in the boiler will gradually increase, provided no portion is supposed to escape through the safety-valve or otherwise. This increasing pressure will gradually accelerate the velocity; and finally, when the engine attains her permanent speed, the quantity of steam consumed in the cylinder and supplied through the steam-pipe, must evidently correspond with the quantity evaporated by the boiler. Thus the author pretends to introduce a new element into the calculation, viz., the evaporating power of the boiler, which again is to be estimated by the quantity of fire surface; and, the density of steam at a given temperature being, according to the law of Boyle and Mariotte, proportional to the pressure and inversely as the volume, as in the case of gases, the evaporating power is measured by the volume of steam, generated in a given time, multiplied into its pressure. Such a mode of proceeding," continues Mr. Woolhouse,

"does not involve any new doctrine or any principle that had not been laid down by Tredgold in the first edition of his work."

If our theory were really represented by this analysis, we might perhaps agree that it would offer but little difference to that of Tredgold; but on recurring to Chapter XII. of this edition, and more especially to our work *On the Theory of the Steam Engine*, in which the differences between the old theory and our own are pointed out in detail, and for the divers kinds of steam engines, it will be at once recognised that this pretended explanation cannot give the slightest idea of our theory; that a most important principle in it consists in the determination of the pressure of the steam in the cylinder and its introduction in the equations, a point which is not even alluded to in the foregoing explanation; that the old theory, by coefficients or such as is used by Tredgold, can lead only to errors; that it gives the load of the engine independently of the velocity of the piston, supporting therefore that the engine will always move the same load at any velocity; that it gives the vaporization for a known load and velocity, independently of the load, so that a greater load would not require a greater vaporization; that it affords no means of calculating the velocity of an engine with a given load; while our own gives, without the least difficulty, the means of calculating the velocity, and also the load and vaporization, in accordance with the facts and principles; that in applying the two theories to the same engine, the results are so widely different that, in some cases, the old theory gives twice or three times the result of our own, as will be seen in the work

alluded to; that our theory explains completely the effects of the atmospheric engine, which could not be calculated, and those of the Cornish engines, which were so unaccountable in the old theory, that the effects related to have been produced by those engines, were reckoned completely false by many engineers in Great Britain; finally, that our theory gives the means of ascertaining the velocity, load, expansion and counterweight, which produce the maximum useful effect in a given engine, a research which was totally impossible and even inadmissible in the old theory. All these differences have escaped Mr. Woolhouse, but they seem to have been noticed by the engineers of the Corps Royal des Ponts et Chaussées, in France, who, in 1839, voted a gold medal to the theory objected to by Mr. Woolhouse. We therefore refer this author to a more attentive perusal of the work which he criticises.

There has also appeared in the *Athenæum*, on the subject of the *Theory of the Steam Engine*, an anonymous paper, on which we cannot help saying a word. The author of this paper, who, whatever he may say to the contrary, possesses but a very superficial knowledge of these matters, affirms it to be needless to undertake new inquiries on the steam engine, since he knows all that is to be known on the subject. He even deems it "absurd" to attempt to ground the calculation of the effect of steam engines on the production of steam in their boiler! A writer whose ideas on this subject are so clear and so profound, has indeed a right to cut questions short, and set himself up as defender of British engineers, whom he declares to be attacked in their honour,

by the very fact of new inquiries on the subject of the steam engine. With such feelings as these, the most foreign to true science, the article is written. As beyond this, however, the author enters into no scientific discussion, and as, too diffident to take on himself the responsibility of his own judgments, he rests modestly under the shelter of his incognito, and has even carried the anonymous system so far as to make in public, to the author whom he has attacked in secret, demonstrations of esteem, the motives of which all may appreciate at their real value, we think ourselves excused from stopping to answer him any further.

Finally, Mr. Josiah Parkes has just published, in the *Transactions of the Institution of Civil Engineers of London*, vol. iii., a long paper in which he undertakes the determination of a coefficient or numerical relation, representing in mass all the divers resistances which locomotive engines have to overcome in their motion, so as to render useless all separate research, relative to the value of friction, resistance of the air, &c. With this view he enters into a long discussion on the experiments of the *Treatise on Locomotive Engines*, and on all the experiments on the same subject published by divers engineers; and to demonstrate the difficulties insurmountable, in his opinion, and the uncertainty, attending researches of this kind, he indicates divers verifications which, as he says, these experiments ought to satisfy. As the author gives on the subject a great number of arithmetical calculations, the errors of which might not be perceived at a first glance, we shall here enter, with some detail, into the examination of his pretended verifications.

On seeing the *fundamental* errors on which his reasoning and his calculations are grounded, the inaccuracy of the results at which he has arrived will at once be recognised.

1st. Mr. Parkes proposes to calculate the pressure at which the steam was necessarily expended in the cylinder of each engine submitted to experiment, in order afterwards to compare that pressure with the pressure resulting from the totality of the divers determinations of resistances exerted against the piston, according to the *Treatise on Locomotive Engines*. With this view, he seeks, from the velocity of the engine, the number of cylinders-full of steam which were expended per minute. Comparing the volume thus obtained to the volume of water vaporized in the boiler, he concludes the *relative* volume of the steam during its passage into the cylinder; and finally, recurring to the Table of the relative volumes of steam under divers pressures, contained in the *Theory of the Steam Engine*, he concludes the pressure which the steam must necessarily have had. This is conformable to the theory developed in the *Treatise on Locomotive Engines*, which, in fact, Mr. Parkes entirely adopts. But to perform this calculation, Mr. Parkes takes the average velocity of the whole trip from Liverpool to Manchester, and from that velocity he pretends to deduce the *mean pressure* in the cylinder during the same trip. Now it will be easy to prove by an example that this mode is altogether faulty.

Suppose, in effect, the engine ATLAS have travelled a distance of 30 miles in an hour and a half, vaporizing 60 cubic feet of water per hour. As the wheel of the engine is 5 feet in diameter, or 15·71 feet in circumference, as there are two double cylinders-full of steam expended at

every turn of the wheel, and as the capacity of those two double cylinders, including the filling-up of the steam-ways, amounts to 4·398 cubic feet, it follows that the volume of the steam which passes into the cylinders per mile performed, or per distance of 5280 feet, is $\frac{5280}{15{\cdot}71} \times 4{\cdot}398 = 1478$ cubic feet.

This premised, when Mr. Parkes refers to the average velocity of the whole trip, to value the pressure in the cylinder, as that velocity was 20 miles per hour, and as the vaporization at the same time was 60 cubic feet of water per hour, he finds for the ratio of the volume of the steam expended to the volume of water, $\frac{1478 \times 20}{60} = 492{\cdot}7$. And consequently, recurring to the Table of the relative volumes of steam under different pressures, he obtains for the corresponding total pressure 56·66 lbs. per square inch; and, deducting the atmospheric pressure, he obtains for the effective pressure, 41·95 lbs. per square inch.

But to show that this mode of calculating, from the average velocity, can only lead to error, let us suppose that, by reason of the divers inclinations of the portions of the railway, the first 15 miles have been traversed in half an hour, and the other 15 miles in an hour, which still makes 30 miles in an hour and a half; as 30 cubic feet of water will have been vaporized in the first half hour, or during the passage of the first 15 miles, and 60 cubic feet of water during the next hour, or in the passage of the last 15 miles, it is plain that the volume of the steam will have been respectively in each of those times, $\frac{1478 \times 15}{30} = 739$, first, and

afterwards $\frac{1478 \times 15}{60} = 369{\cdot}5$. Whence results, according to the Table, that the effective pressure of the steam will have been successively 21·62 and 62·95 lbs. per square inch.

Thus, during the first half hour the effective pressure will have been 21·62; during the second half hour it will have been 62·95, and during the third again 62·95. Consequently, taking account of the time during which the pressure has had these respective values, it is plain that the mean effective pressure in the cylinder will really have been $\frac{21{\cdot}62 + 62{\cdot}95 + 62{\cdot}95}{3} = 49{\cdot}17$ lbs. per square inch, and not 41·95 lbs. per square inch, as it is given in Mr. Parkes's calculation; which, by the fact, supposes all the portions of the trip to have been performed in equal times. In this case, therefore, which has nothing in it but what is very ordinary, there would be an error of 7·22 lbs. per square inch out of 41·95; that is, an error of more than $\frac{1}{6}$ on the effective pressure of the steam. It is evident that the calculation, such as Mr. Parkes makes it, is exact only for portions of road composed of one inclination or travelled with *uniform* velocity, and that it cannot apply to the total passage of a line composed of different inclinations. For further elucidations on this head we refer to Chap. XVII. of this work, relative to inclined planes, and to Chap. XII., in which all the experiments considered by Mr. Parkes are calculated.

2nd. We have just shown a first error which Mr. Parkes introduces, as a fundamental basis, in his calculation of the pressure of the steam in the cylinder. But he does not

stop there. In the Table of experiments on the vaporization of the engines (Chap. V. Art. IV. § 1 of the *Treatise on Locomotive Engines,* 1st edition, and page 253 in this), we have given the average velocity of the engines during each trip; and that velocity is obtained simply by dividing the whole distance performed by the time employed in performing it, as is seen in the Table in question. It would be natural then for Mr. Parkes, who, as has been said above, is satisfied with average velocities in his calculations, to take those which are given in the Table; but instead of that, he augments almost all the velocities about $\frac{1}{5}$. Thus, for instance, the VULCAN, which travelled 29·5 miles in 1 hour 17 minutes, and whose average velocity in consequence appeared to be 22·99 miles per hour, had, according to him, a velocity of 26·90 miles per hour. The velocity of the VESTA rises from 27·23 to 31·60 miles per hour, and so of the others. The critic falls into this new error because, in the *Treatise on Locomotive Engines,* (Chap. IX. § 2, 1st edition, and p. 311 in this), in speaking of fuel, it is said that, when the engines ascend without help the inclined planes of the Liverpool and Manchester Railway, the surplus of work, thence resulting for them, equals, on an average, the conveying of their load to $\frac{1}{6}$ more of distance, and Mr. Parkes logically concludes from this that the *velocity* of the engine must be by so much increased. So that if an engine perform 1 mile in 4 minutes, ascending a plane inclined $\frac{1}{89}$, which renders nearly five-fold the work of the engine, it would follow, from this calculation, that the velocity would not have been 15 miles per hour, but $15 \times 5 = 75$ miles per hour, since the quantity of work done would

have been five-fold! Mr. Parkes's error proceeds from his having applied to the *velocity* a correction which belongs only to the *work* done, and, as a consequence, to the *fuel*.

But on examining what effect results from this substitution of the imagined velocity of Mr. Parkes for the observed velocity, it will be remarked, that whenever an engine is obliged to ascend without help one of the inclined planes of the Liverpool and Manchester Railway, it exerts in that moment, as we have said, an effort about five times as great as upon a level, and draws its load less rapidly. One would deem it then allowable to conclude that the average pressure of the steam in the cylinder must be augmented, since, during a certain portion of the trip, the effort is greater, and that the *useful* effect per unit of time must be diminished, since during the same time the useful load is drawn at less velocity. But no. Mr. Parkes's calculation, by augmenting the apparent velocity of the engine, demonstrates that, in this case, the average pressure in the cylinder becomes on the contrary much *less* and that the useful effect becomes much *greater*. So that the error committed produces itself here in the two opposite ways.

With these elements Mr. Parkes establishes the *whole* of his calculations and of his Tables, to the very end of his paper; and as, to augment the evil, this pretended correction happens to be made on one portion of the experiments, without being made on the rest, there results an inexplicable confusion in all the calculations. Thus also it happens that his determinations of the horse-power produced per cubic foot of water vaporized, or of the quan-

tity of water employed to produce the power of one horse, and all the consequences thence derived, are in every way erroneous.

3rd. After having thus calculated *very exactly* the pressure of the steam in the cylinder, Mr. Parkes compares the result which he has obtained, with the total pressure on the piston resulting from the partial resistances suffered by the engine, according to the *Treatise on Locomotive Engines;* and as, in the first edition of the work, the author had confined himself to mentioning the pressure against the piston due to the action of the blast-pipe, without making any experimental research on the subject, Mr. Parkes takes the difference between the two results, as necessarily expressing the pressure due to the blast-pipe; and he demonstrates the inaccuracy of it. Here we perfectly agree with him; for, besides the errors already pointed out in his research of the pressure of the steam in the cylinder, every thing variable that can occur in the different data of resistance, now passes to the account of the pressure due to the blast-pipe, and must necessarily come to falsify the calculation of it. Thus for instance, in the experiments made with the FIREFLY, the boiler lost water by the tubes, and there resulted an apparent vaporization greater than the true one. A part of the difference between the calculated and the observed pressure was therefore to be attributed to that cause, though it could not be accurately measured; but, by the calculation of Mr. Parkes, it all passes to the account of the pressure due to the blast-pipe. Similarly, the resistance of the air, then imperfectly computed in the total resistance for an average velocity of about 12 miles per hour, is found, in all

cases of greater velocity, to augment considerably the pressure due to the blast-pipe, and on the contrary to diminish it in all cases of less velocity. A contrary or a favourable wind, waggons well or imperfectly greased, &c., necessarily produce similar effects. Thus circumstances, combined with the errors already introduced into the calculation, raise or lower that pressure to all imaginable degrees; and it will readily be imagined that such a determination cannot be exact.

4th. Mr. Parkes has observed, in the experiments of the *Treatise on Locomotive Engines*, and particularly in two of them, made on the LEEDS engine, and quoted in the *Theory of the Steam Engine*, that the useful effects produced by the same quantity of water vaporized varies according to different circumstances; and he is amazed at it; for, as he affirms, the useful effects produced by the same quantity of water vaporized, in the same time and under the same pressure in the boiler, ought in all cases to be identical. But this again is merely an error of the critic; for if we suppose a locomotive engine drawing a heavy load at a small velocity, since it is only at a small velocity that the engine has to overcome its friction, as well as the atmospheric pressure against the piston, and, above all, the resistance of the air against the train, it follows that, out of the quantity of total work executed, there will be but a trifling portion lost in overcoming those resistances; but if, on the contrary, we suppose the same engine performing precisely the same quantity of *total* work, but drawing a light load at a great velocity, it is obvious that a much greater part of the work done will be absorbed in moving, at that velocity, the resistance which represents

the friction of the engine, as well as the atmospheric pressure against the piston, and in overcoming the resistance of the air, which increases as the square of the velocity; and consequently there will remain a much smaller portion of it applied to the producing of the useful effect. Hence, in the two cases considered, the useful effects produced by the same quantity of water vaporized, so far from being identical, will, on the contrary, be very different from each other. Mr. Parkes may, besides, satisfy himself on this point, by perusing the *Theory of the Steam Engine*, in which he will find numerous examples of steam engines, in which the useful effect of 1 cubic foot of water varies in very wide limits, according to the velocity of the motion or the load imposed on the engine. Thus Mr. Parkes's reasoning errs again by the basis itself.

5th. But there is another principle to which Mr. Parkes would subject all the observations of vaporization of locomotive engines. He remarks that in the two experiments above cited, the total resistance opposed to the motion of the piston is different in the two cases. Consequently, says he, the quantities of water vaporized by the engine in the same time must be in proportion to the pressures observed in the cylinder, and the experiments must satisfy this condition.

To establish this new principle, Mr. Parkes recurs to the Treatise on Locomotive Engines itself. He quotes a passage in which, supposing the same engine travelling the same distance with two different loads, the author says positively that the distance travelled being the same in both cases, the number of turns of the wheel, and consequently

the number of strokes of the piston given by the engine, that is to say, the number of cylinders-full of steam, or, finally, the total volume of steam expended, will also be the same in both cases; whence results that the same volume will successively have been filled with two steams at different pressures, or, in other words, at different densities; and consequently the quantities of water which have served to form those steams will be in proportion to their respective pressures (Chap. IX. § 1, 1st edition). Thus, this passage establishes very distinctly that the quantities of water vaporized, *for the same distance*, are in proportion to the pressures of the steam in the cylinder. But what does Mr. Parkes conclude from this? Why, that the quantities of water vaporised *in the same time* are in proportion to the pressures in the cylinder. Now, it happens to be just the contrary; for if we suppose, by way of example, the two pressures to be in the ratio of 2 to 1, the volumes of water vaporized for the same distance will also be as 2 to 1; but if the time employed in performing the distance in question be two hours in the first case and one hour in the second, it is plainly the quantities of water vaporized in two hours and in one hour respectively, which will be one to the other in the ratio of 2 to 1, so that the vaporizations per hour, or *in the same time*, will be equal instead of being in the ratio of the pressures. Thus it is clear again that Mr. Parkes's principle rests but on a new error, which consists in making a confusion between the vaporizations for the same distance and the vaporizations for the same time.

6th. A final observation of Mr. Parkes is this, that in some experiments, the locomotive engines produced, for

the same quantity of water vaporized, a greater useful effect than several stationary high-pressure steam engines, or even than several condensing steam engines; and he considers this result as a proof of the uncertainty of those observations; for, says he, the locomotive engines having to contend with the pressure arising from the blast-pipe, which the high-pressure engines have not, and also with the atmospheric pressure, neither of which resistances the condensing engines have to contend with, it is incontestable that they cannot even produce equal effects, much less superior ones. But this reasoning is as unfounded as those we have already noticed; for since the useful effect of steam engines for the same vaporization, diminishes as the velocity of their motion increases, which is found developed, either in the present work, Chap. XII., or in the *Theory of the Steam Engine*, it is easy to conceive that a locomotive, working, for instance, at its maximum useful effect, that is to say, with its maximum load, and consequently at a very small velocity, at which the pressure due to the blast-pipe and the resistance of the air are nearly null, can produce a useful effect greater, nay much greater than a stationary high-pressure engine, working on the contrary with a light load and a great velocity. The same inferiority of effect, relative to a locomotive, may also occur in a condensing engine, because an engine of that system, working, for instance, at 16 lbs. pressure per square inch in the cylinder, and condensing the steam to 4 lbs. per square inch *under the piston*, where the pressure is always greater than in the condenser, loses, by that fact alone, a

quarter of the power that it applies; whereas a locomotive working at 5 atmospheres in the cylinder, and at a very small velocity, which renders almost null the pressure due to the blast-pipe, suffers, by the opposition of the atmospheric pressure, a loss equal to but $\frac{1}{5}$ of its total power. Hence, definitively, in the latter engine, the counter-pressure against the piston destroys a smaller portion of the total power applied, and consequently, without even noticing the difference of the friction of the two engines, or entering into any other consideration relative to the velocity, it is conceivable that the useful effect of the locomotive may be found the greater.

But if a more complete proof be desired, it will be easy to furnish it; for the relative volume of the steam at 16 lbs. per square inch, being 1672 times that of the water, it is plain that if S represent the number of cubic feet of water vaporized per minute in the boiler, and if a represent the area of the cylinder expressed in square feet, 1672 S will be the volume of the steam generated per minute, whence results that $\frac{1672\,S}{a}$ will be the velocity assumed by the piston of the engine working at that pressure. Moreover, the *effective* pressure of the steam or the load which the piston can support, is $16 - 4 = 12$ lbs. per square inch; which gives $12 \times 144\,a$ for the total resistance supported by the piston. Thus, in the condensing engine, the effect produced by the number S of cubic feet of water, is expressed by $1672 \times 12 \times 144\,S = 20064 \times 144\,S$. Calculating in the same manner the case of the locomotive engine, we find that the effect it produces for the same

vaporization S, working at the total pressure of 75 lbs. per square inch, or at the effective pressure of 60 lbs. per square inch, is $381 \times 60 \times 144\,S = 22860 \times 144\,S$. Therefore, finally, its useful effect, per cubic foot of water vaporized, will exceed that of the condensing engine, and this again is a circumstance, examples of which will be found in the *Theory of the Steam Engine.*

Thus this new peremptory condition which the experiments ought to satisfy is as unfounded as the former ones. It will be remembered, besides, that the velocities employed by Mr. Parkes, for locomotive engines, being nearly all considerably augmented, as has been explained above, he must necessarily arrive at exaggerated results, for the effects which he supposes to have been produced by those engines.

It is remarkable, finally, that in applying the preceding considerations to all the experiments published on locomotives by different engineers, namely: Messrs. R. Stephenson, N. Wood, E. Wood, and Lardner, Mr. Parkes finds that the conditions to which he proposes to subject those experiments are not verified in them. Such a result ought to have put him on his guard against the validity of his own arguments: but the want of using equations, which facilitate so much accuracy in mathematical reasoning (and the author accounts for it in telling us that he is more accustomed to handle the hammer than the pen), causes him to heap errors on errors, combining and complicating them unaware, till he arrives at a point where he does not produce a single result that is not erroneous.

There is matter of surprise in the numberless errors contained in the paper of Mr. Parkes, and of which we have noticed merely the principal ones; but on inquiring what was the end he had proposed to himself, what was to be the definite consequence of his labour, one is yet much more surprised. Collecting all the erroneous results which he has obtained, Mr. Parkes forms a Table in which he sets in view, on one side, the vaporization effected by the engine, and on the other side, the useful and the gross effect produced; but to the latter he gives the name of *momentum.* Then, comparing the vaporization to the effect produced, and taking an average upon all the experiments which he has collected from all the works published on the subject, he presents, as the result of his labours, the following conclusion, which he proposes to substitute in place of every other kind of research on locomotive engines.

When the velocity of a locomotive engine is augmented in the proportion of 1·52 to 1, the vaporization necessary to produce the same effects varies in the following proportions:

To produce the same *momentum* (the same gross effect, weight of waggons and engine included), in the proportion of 1·42 to 1, or in a proportion something less than that of the velocities; to produce the same *commercial* gross effect (the same gross effect including the weight of the waggons), in the proportion of 2·43 to 1, or nearly as the squares of the velocities; to produce the same *useful* effect, in the proportion of 3·11 to 1, or nearly as the cubes of the velocities.

This is the definitive result which Mr. Parkes has attained, and the help of which seems to him to render it needless henceforward to seek to determine either the friction of the waggons, or that of the engines, or the resistance of the air, or any thing in fact that may influence the effects produced; researches which appear to him to offer insurmountable difficulties. Possessed of the *wholesale* result of Mr. Parkes, nothing more will be needed. Does any one wish, for instance, to know what load a given engine will draw at 25 miles per hour on a given inclination? to know what velocity it will assume with a load of 60 tons? to know what is the maximum of useful effect that it is capable of producing? to know what proportions must be given to it, in order to obtain desired effects? Why, having recourse to Mr. Parkes's result, the solution of all these questions is self-evident!

It is evident, on the contrary, that Mr. Parkes's rule, even were it exact instead of being founded on erroneous calculations, could lead to but one thing, namely, that of finding the gross or useful effect produced by an engine at the velocity of 30 miles per hour, when the same effect is known at the velocity of 20 miles. But, even then, making use of so rough an approximation, in which all is thrown in the lump: friction of the waggons, friction of the engine, resistance of the air, resistance owing to the blast-pipe, &c., the result could never be depended on. Assuredly, calculations like these do not tend to the progress of science; they would rather lead it back again to its first rudiments. For this reason we persist in our belief that the only means of calculating locomotive engines, is to

endeavour to determine, as exactly as possible, each of the resistances which oppose their motion, and by taking account of the value of each of those forces in the calculation, we may in every case attain a valuation really founded in principle, of the effects of every kind that are to be expected from them.

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A PRACTICAL TREATISE

ON

LOCOMOTIVE ENGINES.

CHAPTER I.

DESCRIPTION OF A LOCOMOTIVE ENGINE.

ARTICLE I.

DETAIL AND DISPOSITION OF THE PARTS.

Sect. I. *Of the Boiler.*

The plan adopted in this work will, it is hoped, render it both clear and methodical.

We shall begin by a succinct description of a locomotive engine, in order first of all to set before the eyes of the reader the machine which is the subject of consideration.

We shall then explain the laws which regulate the mechanical action of the steam, and describe the instruments in use to measure its pressure; which will make known the agent employed to produce the motion of the engine.

Our attention will afterwards be directed towards the resistances which the engine in its motion has

to overcome, so that we shall successively endeavour to determine as well the resistance of the waggons as that which belongs to the engine itself, either when it moves alone or when it draws a load after it.

With these primary data we shall pass to the general theory of the motion of locomotive engines, and shall lay down the formulæ by which to determine, *a priori*, either the speed the engine will assume with a given load, the load it will draw at a given speed, or the proportions which are to be adopted in its construction, in order to obtain any intended effect.

We shall then have to consider several additional dispositions proper to the engine, which may exercise more or less influence on the expected effects; and we shall also treat of some external circumstances, the result of which may be of the same nature.

Lastly, we shall show the engine's consumption of fuel with given loads, and every other kind of expenditure to which it gives rise.

These inquiries give the solution of all the most important questions concerning the application of locomotive engines to the draught of loads. They will sometimes be necessarily subdivided into several branches, and require calculations and theoretical illustrations, of more or less extent, though always plain and easy, and a series of experiments more or less numerous; but we shall take care to main-

tain, all through our work, the classification we at present lay down. We begin then by the description of the engine.

Plate I. represents a six-wheel locomotive engine, followed by its tender. Plates II. and III. represent a locomotive with four wheels. The mechanism of these engines is sufficiently simple for a short description to make their mode of acting understood; which is the only object here intended. Moreover, whatever this first cursory view may leave imperfect will be found illustrated by the developements which we shall have occasion to give in the course of the work.

The principal parts of the engine are: the fire-place and boiler, which constitute the means of raising the steam; the slides and cylinders, which are the means of bringing into action the elastic force residing in that steam; and the cranks and wheels, by means of which the motion is transferred from the piston to the engine itself. After having described those principal parts, we shall pass to some others of less importance, and then show the particular place each of those parts occupy in the engine.

Figure 5 gives a complete idea of the boiler.

It shows the body of the machine, composed of three distinct compartments. That on the right, or in front of the engine, and which is surmounted by the chimney C, is called the smoke-box. It is separated from the two others by a partition *tt*. The two other compartments together form the

boiler: the hinder one is called the fire-box, and the middle one, or cylindrical part, is the boiler properly so called. Both the latter compartments are filled with water to a certain height *cd*, but part of their internal space is occupied by the fire, as will be explained.

In the hindmost compartment is placed a square box *e*, which contains the fuel, or forms the fire-place of the engine. Between the sides of that box and those of the compartment in which it is contained, a space *qq* is left, which communicates freely with the remainder of the boiler, and which is consequently filled with water. The fire-place is supported in the corresponding compartment, and joined to it by strong bolts, having the advantage of giving solidity to that part of the boiler which, not being rounded, offers less resistance than the cylindrical parts.

The fire-place *e*, being thus placed in the middle of one of the compartments of the boiler, would be surrounded on all sides with water, were it not for the aperture *l*, which forms the door of the fire-place, and the bottom, *nn*, of the box, which is occupied by a grate, one of the bars of which is represented at *nn*. This grate is more plainly shown in fig. 6, which represents the same fire-box seen in front.

Near the door *l*, and on the engine, is placed a strong supporting plate of iron, represented in figs. 1 and 2, by BB. The use of this plate is for

the engine-man to stand upon. Directly behind the engine comes the tender-carriage for coke and water, so that it is easy for the fireman to throw coke on the fire by the door *l*, and to let water pass into the boiler, whenever it may be necessary. This supply of water takes place by means of a forcing-pump, put in motion by the engine itself, and which will be spoken of hereafter.

The lower part, *nn*, of the fire-place is occupied, as we have said, by a grate, and remains consequently open, admitting the external air required for the combustion of the fuel. The coke thrown into the fire-place falls on the grate and is supported by it. When the fire is lighted, and the door is shut, the flame of the fuel remains confined in the fire-place. It would have no egress if a number of small tubes or flues $e'e''$, the disposition of which is better seen in fig. 6, were not to lead the flame to the chimney, after passing through the whole length of the second compartment or cylindrical part of the boiler.

From this construction it will easily be conceived, that as the fire is shut up in the fire-box, and completely surrounded with water, none of its calorific parts are lost. Afterwards, the flame, in its way to the chimney, divides itself among all the small flues above mentioned. It thus traverses the water of the boiler, having a considerable surface in contact with it, and only escapes after having communicated to the water as much as possible of

the caloric it contained. Once arrived at the extremity e'' of the tubes, the flame spreads itself in the smoke-box, and escapes freely through the chimney C.

We see thus the heat applied here in two distinct manners. All the water which surrounds the fire-place is in contact with the ignited fuel; and the water which is placed in the middle compartment is in contact with the inflamed gases which issue from the fire-place. We shall refer again to this distinction, in treating of the vaporization of the boilers, and we shall endeavour to ascertain if the effects produced in each compartment differ from each other.

To this form of boiler is to be attributed all the astonishing power of locomotives at the present day. It permits, in fact, exposing a very large extent of surface to the action of the fire, and consequently to develope a considerable quantity of steam, using at the same time a boiler of very small dimensions, which is necessary for engines which have to carry their own weight with their load. And, moreover, it must be remarked that all the effect produced by the tubes is obtained without burning any more coal, and in merely employing the caloric which would otherwise be lost. As in the action of locomotives, all finally depends on the quantity of steam that can be developed in the boiler in a given time with the least possible expense, it will readily be conceived that this invention is unquestionably the

most important that has been introduced into the construction of locomotives since their origin.

It may be necessary to observe here, that this form of a boiler, with tubes, is a French invention. This ingenious idea belongs to M. Seguin, civil engineer and manufacturer in Annonay.[1]

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[1] M. Seguin's patent bears the date of the 22nd of February, 1828; and it was not until April 25, 1829, that the committee of directors of the Liverpool Railway called the attention of the English mechanicians towards locomotive engines, by proposing a prize on the subject. On October 6, of the same year, 1829, and not before, appeared the *Rocket* engine of Messrs. Stephenson and Booth, the principle and even the form of which differ in no way from M. Seguin's patent. Without then by any means detracting from Mr. Booth's merit in having also conceived that ingenious idea, the prior claim rests, nevertheless, with the French engineer.

The fact may be easily verified in England, by looking for a description of the patent in some of the following works, which are certainly to be found in the British Museum and other chief English libraries: *Annales de l'Industrie Française et Etrangère, ou Recueil Industriel et Manufacturier, année* 1828; *Bulletin de la Société d'Encouragement pour l'Industrie Nationale, année* 1828; *Description des Machines et Procédés consignés dans les Brevets d'Invention, de Perfectionnement et d'Importation, publiée d'après les Ordres du Ministre de l'Intérieur et du Commerce.* This last work only gives the description of expired patents; so that M. Seguin's will be found in the year 1838.

In an American edition of Wood's work on Railways (page 338) we find, that in 1825 Mr. John Stevens, of Hoboken in the State of New Jersey, constructed and employed a locomotive engine, the boiler of which consisted entirely of tubes of very small diameter filled with water. But as in the boilers we speak

SECT. II. *Of the Action of the Cylinders.*

The second important part of the engine is the apparatus of slides and cylinders. Fig. 5 is also designed to show its disposition.

In the upper part of the boiler, that is to say, in the part occupied by the steam, is a large tube $VV'V''$, called the steam-pipe. It is open at one end V, and leads out of the boiler. By this tube the steam is conducted into the cylinders. At V', in the interior of the tube, is a cock or regulator, the handle T of which extends out of the engine. By turning that handle more or less, the passage for the steam may be opened or shut at will.

The steam, being generated in great abundance in the boiler, and unable to escape out of it, acquires a considerable degree of elastic force. If at that moment the cock V' is opened, the steam, penetrating into the tube by the aperture V, follows it to the entrance v of the slide-box. There a sliding valve x, which moves at the same time with the engine, opens a communication to the steam successively with each end of the cylinders, and this steam drives the piston alternately from one extremity of the cylinders to the other. The cylinders are

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of, it is the flame and not the water that fills the tubes, which totally changes the principle of their construction, the fact reported by the American editor does not disprove the remark established above.

placed horizontally at the bottom of the smoke-box, where the passage of the flame and the sides of that box protect them against the condensing effect of the cold air, and keep them in a proper degree of heat.

The direction of the arrows in the figure marks the line of circulation followed by the steam, from its entrance at the aperture V, as far as the slide-box. In the situation in which the slide is here represented, passage 1 is open to the steam, and consequently the piston is pushed in the direction of the arrow. At the following instant, passage 2 will be open in its turn, and the piston will be pushed the contrary way. When the steam has produced its effect, it passes into the tube *v′*, and is conveyed by it to the chimney, through which it escapes into the atmosphere.

The introduction of the steam takes place at V, in a dome called the steam-dome, purposely elevated, that the jolting of the engine and the ebullition may not cause the water of the boiler to get into the opening V.

Sect. III. *Of the Cranks and Wheels.*

The piston-rods being set in motion according to the foregoing explanation, and sliding in guides which prevent any deviation from a rectilinear horizontal motion, communicate a rotatory movement to the axle of the two large or drawing

wheels of the engine. The transformation of the alternate motion into a circular one, takes place after the manner of the common foot spinning-wheel, by means of a crank in the axle. This effect is clearly represented in fig. 5. There the steam may be seen forcing alternately the piston backwards and forwards, and turning the crank *yz*, and at the same time the axle and the wheel which is fixed to it. However, as in the motion of a crank, there are two points in which the alternate force that puts it in motion has no greater tendency to move it in one direction than in another, which takes place when the radius of the crank happens to be in the direction of the alternate motion, the two cranks, respectively corresponding with the two pistons, are placed at right angles to each other. By that means one of the two has always its full effect whenever the other ceases to act, and the power of the engine does not vary. The two cylinders being placed, as we have already said, in the lower part of the smoke-box, the piston-rods communicate directly under the engine with the two cranks, as appears in the figure. The crank-axle being set in motion, the wheels, which form one body with it, turn at the same time, and the engine is propelled in the same manner as a carriage which is set agoing by turning the wheels round by the spokes.

The only fulcrum of the motion being in the adhesion of the wheels to the rails that support

them, which adhesion causes them to advance instead of slipping round, it might appear doubtful whether, on such an even surface as the rails of a railroad, the engine could advance by means of the sole rotatory motion imparted to its wheels, particularly when the engine has to draw a considerable weight. But experience proves, that however slight the adhesion of a wheel to a well-polished rail may appear to be, as, on the other hand, the power required to draw a load on a railroad is very small, that adhesion is sufficient, and the engine progresses, followed by its whole train.

In ordinary cases the adhesion of two wheels is sufficient; particularly with engines the weight of which is so distributed that the drawing-wheels bear a large portion of it. When a great power of adhesion is required all the wheels are made equal. In that case, if necessary, the wheels of the same side may be connected together by metallic rods placed on the outside of the wheels. One of these connecting-rods is represented in fig. 35, Plate III. C is the prolongation of the axle beyond the wheel. The crank-arm C*o* is fastened to that prolongation of the axle, and must necessarily turn with it. The point *o* is a ball and socket joint; *m* is a cotton-wick syphon, by which the oil is fed into the joint; *nn* are keys designed to lengthen or shorten the rod, which at its opposite end is joined in the same manner to the crank-arm of the other wheel. The natural result of this is, that when the wheel or the

axle C turns, it carries along with it the crank-arm C*o*, and thus communicates the same motion to the other extremity of the connecting-rod, and by it to the crank-arm of the second axle. Thus the motion of the machinery is communicated by the two working wheels to the others, and the engine then adheres by all its wheels.

In order that, while in motion, the engine may not slip off the rails, which, we know, are iron bars projecting above the ground, the wheels have, on the inner side, a flange that prevents any lateral motion. But as, on the other hand, that flange ought not to be in danger of constantly rubbing against the side of the rail, the tire of the wheel is not exactly cylindrical, but slightly conical. Its diameter is a little larger on the side of the flange than on the outward side; the consequence of which is, that, supposing the engine were to be for a moment pushed to the left, the left wheel, resting on its broadest part, would pass over more way than the right wheel, and by that means bring the engine back to its true place between the rails. Wheels of such a form may be seen in figs. 3 and 4.

SECT. IV. *Of the Safety Valves.*

The three preceding points form the foundation of the play of the engine; the other parts are merely accessory, that is to say, essential only to the setting of the former in action. The boiler has

two safety-valves E, F (figs. 1 and 2), one of which, F, is sometimes shut up in a box, to put it out of the reach of the engine-man, and to prevent him from overcharging it, as he might be tempted to do in order to obtain from the engine a greater effect, even at the risk of damaging it. More commonly, however, this precaution is given up, on account of its inconvenience.

The object of these valves is to let the steam escape into the atmosphere, as soon as its elastic force attains a limit beyond which it might be dangerous to the boiler. They may also, by being properly loosened, be used to measure the pressure of the steam; but as this point demands some developement, we shall hereafter make it the subject of a chapter.

Sect. V. *Of the Water-Gauge.*

A gauge is likewise fixed to the engine to show at what height the water stands in the boiler. This gauge is a glass tube, *mn* (fig. 7), enchased at both its ends in two verrels *aa*, with cocks communicating with the interior of the boiler and appearing outside, as may be seen in the figure. When the two cocks *rr* at top and bottom of the tube are opened, the water penetrates into the tube and takes the same level as in the boiler. The cock S is designed to let that water afterwards run off. This instrument informs the engine-man when the ap-

paratus wants a supply from the pump. As, however, the tubes and other parts of the boiler begin to suffer, that is to say, are apt to crack, when the water gets too low in the engine, there are, for still further surety, on the side of the boiler, two and sometimes three small cocks, placed at different heights; by opening which, one after the other, the level of the water in the interior may be also ascertained.

SECT. VI. *Of the Slides.*

Another important object yet remains to be elucidated. We have said above that the slide-valve admits successively the steam above and below the piston of each cylinder, the result of which is the alternate motion, source of the final progressive motion of the engine. The engine-man then having opened the regulator or cock that admits the steam into the pipes, the steam proceeds from the boiler through the tube *v* (fig. 8) into the steam-chest or slide-box, and, pressing with all its force on the upper part *x* of the sliding-valve, compels it to remain in immediate contact with the plane on which it slides while performing its motion. When the slide is in the situation in which it is represented in fig. 8, the steam takes the way marked 1, acts upon the piston, and pushes it in the direction of the arrow. In the meanwhile, the steam under the piston escapes through the passage 2, which then communicates with the atmosphere by means

of the aperture *e*. When this first effect has been produced, the slide, by means of its rod *l*, is pushed in the position marked by the dotted lines. Then, on the contrary, it is the passage 2 which is open to the steam coming from the boiler: it pushes, consequently, the piston in the opposite direction to its first motion, while the passage 1, communicating in its turn with the aperture *e*, gives free egress to the steam that has produced its effect. The alternate motion continues thus: the slide passing from one position to the other, by which it opens and shuts successively the passages or steam-ports, so that the steam may act alternately above and below the piston. The steam is afterwards led to the chimney, as will be explained hereafter, there to augment the current of air by which is caused the draught of the fire.

The motion of the slide is regulated in such wise that, in accompanying the motion of the piston, it nevertheless precedes it by an instant of time; that is to say, instead of opening the passage for the stroke of the piston, just at the moment the piston is about to begin that stroke, it opens it a little beforehand. We shall have occasion to come back to this point, and it will appear that this disposition, favourable to the speed of the engine, may be advantageously employed within certain limits; but that beyond those limits it is prejudicial to the maximum load which the engine is able to draw.

Sect. VII. *Of the Eccentric Motion.*

The alternate motion of the slide is performed by the steam itself. Some attention is requisite to get a clear conception of this.

An eccentric wheel is fastened to the axle, and while the axle turns, the eccentric, drawn along by its motion, pushes and draws alternately the rod of the slide.

This effect is represented in figures 9 and 10. The point O is the centre of the axle, the section of which is here hatched. The point *m* is the centre of the eccentric, hatched in a contrary direction. The axle, in turning, draws the eccentric along with it, and consequently makes the point *m* describe a circle round the point O. In that motion the point *m*, passing successively to the right and the left of the centre O, must necessarily push and draw alternately the shaft L, which acts upon the slides.

On the other hand, the point C representing the extremity or throw of the crank of the axle, which is set in motion by the piston, it will appear that when the steam, pushing the piston from one end of the cylinder to the other, makes the crank revolve half-way round, the axle makes also the half of a revolution round itself; therefore the point *m* describes the half of a circumference round the point O, and consequently the eccentric pushes the slide-rod *l*, from one of its extreme positions to the other, that is, from one end of its stroke to the other.

Thus placed, by this first operation, the slide now admits the steam on the opposite side of the piston. The piston then goes back, makes the axle revolve again half-way round, whereby the slide is brought back to its original position, which suits the next stroke of the piston; and so on.

The effect of drawing and pushing alternately the slide-rod, by means of the rotation of the eccentric, is accomplished by a metallic ring *nn* fixed to the end of the shaft L, and in which the eccentric wheel turns, the surfaces which are in contact being smooth and lubricated with oil. By this arrangement, while the great radius of the eccentric passes, in turning, from one side of the centre to the other, it carries along with it the shaft fastened to the ring, and communicates to that shaft the alternate motion.

By this it will be seen that the eccentric wheel acts here the part of a common crank, for transforming the circular motion of the axle into an alternate motion applied to the slide, on the contrary principle to that which changes the alternate motion of the piston into a circular motion applied to the axle of the engine; but the eccentric dispenses with the crank which would have been necessary in the axle.

However, as by the disposition of the engine the slide-rod is not in the same plane with the axle, the eccentric does not communicate the motion directly to the slide-rod itself, but by means of the cross-

axle L′Kl′, whose fixed point is at K; and the consequence is, that when the eccentric goes back, the slide-rod advances, and *vice versâ*, as may be seen in the figure.

A comparison between the figs. 9 and 10, the difference of which is a quarter of a revolution, will make the above-mentioned effects perfectly intelligible.

By examining the motion of the slide (figs. 10 and 26) it will be seen, that while passing from one of its situations to the other, and when it happens to be in the middle position, there occurs an instant during which both the passages or steam-ports are shut. This effect takes place at the moment the slide changes the passages of the steam, and corresponds with the point where the piston changes its direction. This coincidence can only take place because, setting aside the lead of the slide, the radius of the eccentric is at right angles with the radius of the crank. In fact, the slide is necessarily thus in its middle position, that is to say, changing the communications of the steam, at the same time as the piston is at the bottom of the cylinder, ready also to alter the direction of its motion. This correlativeness of motions is clearly exhibited in the figure.

The particular advantage of the eccentric being thus placed at right angles with the crank is, that the eccentric is in full action when the crank is on its centre, or the piston at the bottom of the cy-

linder: that is to say, that the slide is in its most rapid motion just at the moment that it is to open or shut the steam-ports; which circumstance is necessary, to prevent time being lost in the alternate effect of the steam.

In order that the steam-ports may not begin to close immediately after having been opened, the slide is so disposed, that after having uncovered one of the ports, it continues its motion for a short space before beginning to return. This effect, which is called the travel of the slide, is represented in the figs. 9 and 11. By this disposition the uncovered port remains entirely open while the slide is performing its travel going and coming, and the opposite port continues to be entirely closed. It will be remarked that this part of the motion of the slide is precisely the slowest of its stroke; but as the slide begins to pass again over the steam-ports, it acquires, on the contrary, its greatest velocity, because the eccentric is then in its most rapid motion. This disposition then causes the apertures to be entirely open or closed during the greater part of the time employed in performing each stroke, and to change them as suddenly as possible at the most favourable moment for so doing.

That the travel of the slide may not have the effect of reducing too much the eduction-port *e*, care is taken to make the latter of such width that, notwithstanding the portion of it which is covered by the flange of the slide, it still retains a width

equal to that of each of the other steam-ports. Thus, for instance, the width of the steam-ports is 1 inch each; that of the bars, or separations between the ports, 1 inch; and the eduction-port *e*, 1½ inch. Then, exclusive of the slight overlap of the slide, of which we shall presently speak, the slide may have a travel of ½ inch; for it is plain that in the extreme position of the latter, the eduction-port will never be reduced to less than an inch, which is the width of the steam-ports.

Finally, when the slide is in its mean position, it not only intercepts at once both the steam-ports, as is seen represented in figs. 10 and 26, but it overlaps them by a small flange, the object of which is to remove all possibility of one of the passages ever being open before the other is completely closed. This overlap is usually from $\frac{1}{16}$ to ⅛ inch, and it is plain that, being added to each side of the slide, it diminishes by so much the travel of the latter, as has been said above.

Sect. VIII. *Of the Drivers.*

Until now we have spoken as if there were only one slide, but, having said there are two cylinders, it is clear that there must be a slide, and consequently an eccentric, to each of them. On the other hand, the two pistons, alternating one with the other in their motion, that is to say, acting

upon two cranks perpendicular to each other, as has been explained, the radii of the two eccentrics must necessarily stand also at right angles with each other. This disposition may be seen in figs. 11 and 12, where the piece forming the two eccentrics is represented in front. To make it more clear it is marked by hatchings.

This piece must, as has been said, move with and be carried along by the axle. However, if it were permanently fixed on the axle, its position might suit when the engine is going forward, and not when it is to go backward; for it will be seen that, for these two motions, the eccentric must be fixed in two different positions.

This piece is therefore loose upon the axle, like a pulley on its axis, but it can be fastened to it at will. To that effect it has two apertures, represented at O and O′; and the axle itself carries two pins $r\,r'$, which are called drivers. The eccentric being placed on the axle between the two drivers, it is easy to push it, by means of a lever, either against one or against the other, until the driver enters into the aperture designed for it; so that from that moment the eccentric may be drawn along by the axle. Moreover, if these two drivers be placed in such a manner that one may suit the progressive, and the other the retrograde, motion of the engine, then, by shifting the eccentric from the one to the other, the engine may

be madè to go either forward or backward at pleasure.

There is no difficulty in fixing the place that the eccentric must occupy on the axle, either for the progressive or for the retrograde motion.

Let us suppose, that by pushing the engine gently along the rails, we bring one of the pistons to be just in the middle of the cylinder, and that precisely at the same instant, the crank on which that piston acts is in its vertical position above the axle, as in fig. 5; it is clear that, to make the engine go forward, the steam must push the piston forwards, for then the piston will carry along with it, in the same direction, both the crank and the wheels. Consequently the slide must admit the steam by the port No. 1, or be drawn forward as it is represented in fig. 5, which, by referring to fig. 9, requires that the radius of the eccentric be horizontal, and placed at the back of the axle. This is therefore the point at which the driver must fix the eccentric for the progressive motion.

The engine remaining in the same position, let us suppose that we wish, on the contrary, to dispose it for the retrograde motion. The steam must arrive on the opposite face of the piston, that is, the port No. 2 must be opened to it; which supposes that the slide is pushed backwards, and consequently that the eccentric is in front. It is therefore horizontally, and in front of the axle,

that the eccentric must be fixed by means of the driver.

This is exactly the position of fig. 12. By observing the crank A, we see that while that crank is vertical and above the axle, the driver *r*, and the aperture that receives it, are behind, and hidden by the axle; consequently, the eccentric is horizontal, and in front,—a position which, as we have seen, suits the retrograde motion. The driver *r* is therefore placed for the retrograde motion, since it keeps the eccentric in that position.

To return to the first case, if we now suppose, on the contrary, that the eccentric be pushed against the other driver *r′*, the corresponding aperture of the eccentric being at O′, that is to say, not being in front of the driver, the consequence will be that, the eccentric not stirring out of its place, the axle will have to turn half round before the driver can enter into the aperture. From this it follows, that if we continue to examine the crank A, it will be found to have arrived *under* the axle, while the eccentric will still be in the front, which is the position that suits the progressive motion; for it is the same as that of the crank above the axle and the eccentric behind, which has been explained above.

Thus, we see that the two drivers *r′* and *r*, in figs. 11 and 12, being placed at right angles with each other, and with the cranks of the axle, are in a proper position, one for the progressive, and

the other for the retrograde, motion of the engine; and that by pushing the eccentric, by means of a lever, either on the one or on the other of the drivers, the effect of the steam on the piston will immediately be to carry the engine either forwards or backwards, according to the driver with which it has been thrown in gear. The lever which causes the change of position of the eccentric, is placed in such a manner as to present its handle within the reach of the engine-man, on the plate on which he stands.

Besides these several dispositions, in order that the man who directs the engine may, himself and of his own accord, move the slides independently of the motion of the axle, the shafts of the eccentrics are not invariably fixed to the slide-rods. They are only fastened to them by a notch L′, figs. 13 and 14. By means of a lever acting on the small rod *m′o*, the engine-man can raise the shaft of the eccentric and disengage it from the notch, as may be seen in fig. 14. Then the slides are at liberty to move independently of the axle; and therefore it is easy, by means of two handles represented by PP, in figs. 2, 3, 4, and connected with the slide-rods, to give to the slides the required motion.

In some modern engines, four eccentrics are employed instead of two; namely, two for the progressive motion of the engine, and two for the retrograde; either pair being set according to the direction in which the engine is intended to move.

This arrangement advantageously supplies the place of the drivers, because it is of a surer effect; but as, with respect to explication, it amounts precisely to the same, we shall not here enter into the detail of that construction.

Sect. IX. *Of the Pumps.*

Under the body of the engine are two pumps *p*, (fig. 2,) the use of which is to replenish the boiler with water. Each of them is placed immediately under the piston-rod of each cylinder, and is worked by it. Each pump sucks the water of the tender into the cylinder of the pump, on the one hand, and on the other hand, forces it from the cylinder of the pump into the boiler, in the usual way. By having two pumps the replenishing of the boiler is secured, as, in case one of the two were to get out of order, the other may easily supply its place. These pumps are in continual action; yet they can only force water into the boiler when the cock of the suction-pipe is opened, thereby to let the water of the tender come into the cylinder of the pump.

The valve of these pumps is ingeniously made of a small metallic sphere, resting on a circular seat, on which it always exactly fits. Its action takes place by rising within a cylinder, the sides of which are pierced with four apertures for the passage of the water. One of these valves is represented in fig. 15. The water is introduced through *a*, from

the interior of the cylinder, under the spherical ball which it raises, and is diffused in the body of the pump by the apertures *b b*. This form of a valve never misses its effect; and the pumps which, in the beginning, were continually out of order, are free from that defect, since Mr. John Melling, of Liverpool, first introduced that sort of valve.

Sect. X. *Of the Regulator.*

The regulator, of which we have spoken above, and by means of which the passage leading from the boiler to the cylinders may be more or less opened, is represented in figs. 32 and 33. It simply consists of two metallic disks placed above and exactly fitting each other, both having an aperture of the same size. The inferior disk is immoveable, and shuts the pipe through which the steam escapes. The superior disk is moveable, by means of a handle T, which projects out of the engine; the stem *r* of the handle passes through the moveable disk, and enters the other in its centre, so as to keep both in a right position over each other. In fig. 32, these two disks are distinguished from each other by hatchings running different ways. By moving the superior disk K, with the handle T, circularly on the inferior disk, the two apertures may be brought to correspond exactly with each other, as in fig. 32, and then the passage is entirely open. If only partially moved, as represented by

the dotted lines in fig. 33, the passage is only partially opened; and when the two apertures do not correspond at all, the communication is completely intercepted: when the passage is thus shut, it is the steam itself that keeps the two disks in immediate contact with each other, by pressing with all its force on the superior disk.

This regulator may also be constructed in a different way. It is sometimes made in the form of a common two-way cock, the steam coming from above; but the one described above is most commonly used.

Sect. XI. *Of the Joints or rubbing parts.*

In all the joints of any importance the oil is fed without interruption by means of a cup, with a wick-syphon placed above the joint, as in fig. 35, Plate II. This cup is made in the form of a school-boy's ink-horn, so that the velocity of the motion may not spill the oil; and there is at the bottom of it a small tube, penetrating to the entrance of the joint. A cotton-wick dipping in the oil of the cup passes into the tube, and, sucking continually the oil out of the cup, drops it into the joint without interruption.

Sect. XII. *Of the Fire-grate.*

The grate in the fire-place is not made of a single piece. It is formed of separate bars, which are

placed side by side at the bottom of the fire-place, where they are supported at their two ends. The advantage of this arrangement is the facility it affords of replacing the bars individually by new ones, when they are worn out by the intensity of the fire. Besides, if any accident should happen to the boiler, and make the water run off unexpectedly, thus endangering the engine, the engine-man may, by means of a hook, easily turn the bars upside down, and consequently extinguish the fire immediately by letting it fall on the road, with the bars that supported it. It is also thus that every evening the fire-place is emptied, after the engine has finished its work.

Sect. XIII. *Of the disposition of the different parts.*

We shall complete this description by showing on the whole engine, as represented in figs. 1, 2, and 3, the places occupied by the different parts of which we have spoken.

A, Part of the boiler containing the fire-place.

BB, Stand for the engine-man and his assistant.

C, Chimney of the engine.

D, Place of the cylinders.

E, First safety-valve, with lever and spring balance, as will be explained hereafter.

F, Second safety-valve, constructed in the same manner.

G, Glass-tube.

H, Gauge-cocks.

I, End of the eccentric-rod.

J, Horizontal guides for the head of the piston-rod, so as to ensure its motion in the exact direction of the axis of the cylinder.

K, Cross-axle, communicating the motion of the eccentric-rod to the slide-rod, by means of the arms KL′ and K *l*′, which are fixed upon it. (See figs. 9 and 10.)

L′, Notch for throwing in gear the eccentric-rod with the cross-axle which works the slide-rods.

MM, Rod by means of which the engine-man can raise the eccentric-rod, and throw it out of gear with the cross-axle which works the slides. This is performed by means of the arms *m* and *m*′ connected together. When the engine-man pulls the rod MM, he causes the arm *m*′ to rise, and with it the small rod *m*′*o*′, which lifts the eccentric-rod out of gear with the arm KL′.

N, Handle, by means of which the engine-man pulls the rod MM, so as to produce the aforesaid effect.

PP, Handles to move the slides when they are thrown out of gear with the eccentrics. The handles acting upon the cross-axle Q, move the cross-heads RR, which are fixed to it. This motion is communicated by means of

the rods SS to the cross-heads *rr*, which act upon the axle working the slides.

T, Handle of the regulator, to open more or less the aperture through which the steam passes from the boiler to the cylinders.

V, Steam dome, in which the steam is confined till it can escape through the aperture of the regulator, and penetrate into the cylinders.

U, Man-hole, or aperture closed by a strong iron plate, and large enough to admit a man into the boiler, when necessary.

XXX, Iron knees, by which the boiler is fixed to the frame of the carriage.

ZZ, Springs resting at *aa* on the chairs of the wheels, by means of two vertical pins passing through holes in the frame of the engine. One end of the pin resting on the back of the spring, and the other on the upper side of the chair, the whole weight of the machine is thus supported by the wheels, but through the intermediate action of the springs.

bb, Guides for the chair of the wheel to slide up and down, according as the spring bends more or less under the weight of the engine. The upper part of the chair is scooped out to form a small reservoir for oil. This reservoir, as well as those above mentioned, con-

tains a tube and a syphon-wick, for feeding constantly the oil upon the axle, at its rubbing point with the axle-box.

c, Suction-tube, by which the feeding-pump draws the water from the tender, to transmit it to the boiler. This tube is afterwards continued by another flexible tube made of hemp cloth, but supported within by a spiral spring, and through which the water arrives from the tender to the pumps of the engine, when a cock fixed to the tender is opened.

p, Feeding-pump of the engine, which is constantly set in motion by a connexion with the piston-rod of the corresponding cylinder, but which cannot force any water into the boiler, unless the cock which lets the water come in from the tender be opened.

p′, Handle and rod of the safety-cock of the pump, serving to ascertain whether the water really arrives in the cylinder of the pump. This cock leads without, so that when it is open and the pump is working, a small jet of water may be seen issuing from it, which shows that the pump has its proper effect.

ee, Buffers, or pads stuffed with horse-hair, to deaden the shocks which may be given or received by the engine. Their elasticity is sometimes augmented by means of a spiral spring within them.

f, Cock, by means of which the water which is

sometimes carried from the boiler to the cylinder may be let out.

g, Mud-hole, or opening made in the double casing of the fire-box and closed with a screw-bolt. In withdrawing this bolt, a cleaning-rod may be introduced into the double casing; and, by means of a forcing-pump, water may be injected with force, to cleanse out the clay sediment left by the boiling of the water. This cleaning is usually performed once a week.

h, (fig. 3.) Moveable plate or door of the smoke-box; by opening which, the ends of the tubes of the boiler, the cylinders, the slides, and the steam-pipes leading from the boiler to the slide-boxes, or from the slide-boxes to the chimney, are visible. This door is opened when it is necessary to regulate the slides, as we shall see hereafter.

i, Whistle, by means of which the engine-man announces at a distance the arrival of the engine. It consists of a sort of inverted tumbler, against the edge of which, on turning a cock, the steam is directed. The forcible rush of this causes a sound nearly like that of a boatswain's call. This whistle is also represented fig. 25.

ARTICLE II.

OF THE PRINCIPAL DIMENSIONS OF THE ENGINES.

SECT. I. *Of the dimensions of the parts from which the power of the engine is derived.*

The foregoing description applies to the most modern locomotive engines, such as those we used for our experiments. But to give a more complete idea of them, we must say something of their principal dimensions.

Locomotive engines may be constructed of all sizes and proportions, according to the road on which they are to move and the work to which they are destined. But to show the dimensions that have hitherto been most generally employed, we will give those of the locomotives of the Liverpool and Manchester Railway, remarking at the same time, that the engines most frequently constructed now are those of the largest dimensions, and that the engines having cylinders of 8 or 10 inches diameter are only remains of the old engines of the Company. The Liverpool and Manchester Railway is 4 feet 8½ inches wide from rail to rail, and the velocity does not exceed 30 miles an hour. For railways of greater width, and whereon a greater velocity is intended, engines of larger dimensions have been constructed. The following Table then is not to be regarded as limiting the dimensions of locomotives, but as intended merely to complete the

foregoing description, by making known the most usual proportions, and particularly those of the engines used in the experiments contained in this work.

Dimensions of the Locomotive Engines on the Liverpool and Manchester Railway (1836).

Number of engines.	Diameter of the cylinder.	Stroke of the piston.	Diameter of the wheel.	Weight of the engine.	Effective pressure in the boiler, in lbs per square inch.
	inches.	inches.	feet.	tons.	lbs.
2	8 to 10	17 and 16	5	7 to 8	50
9	11	16	5	8 to 9	50
6	11	18	5	10 to 12	50
2	11	20	5	11 to 12	50
2	12	16	5	11 to 12	50
2	12	18	5	12 to 12½	50
5	12½	16	5	10 to 11	50
1	14	12	5	11½	50
2	14	16	5	12	50
2	15	16	5	12½	50

Most of these engines have now six wheels, two of which, five feet in diameter, are worked by the steam, and four, three feet in diameter, are destined merely to sustain the weight of the engine. Sometimes the six wheels are of equal size, and are all set in action by the steam, by means of connecting-rods which communicate the motion of the driving-wheels to the four others. The advantage of this last disposition is to make the engine adhere to the rails by six wheels instead of two; but a very ingenious apparatus, invented by Mr. John

Melling, foreman of the Company's factory at Liverpool, and of which we shall speak hereafter in Chapter XIV., allows the same advantage to be obtained with wheels of unequal diameter; which besides are more favourable to the convenient arrangement of the divers parts of the engine.

The end proposed in adopting six wheels rather than four is to lessen the wear and tear of the rails by dividing the weight of the engine among six supports instead of four. A second motive also is in view; namely, to prevent all possibility of accident in the event of the crank-axle happening to break. In this case a four-wheel engine would run the risk of going off the rails, but if supported on six wheels the remaining four will necessarily keep it on the line.

Sect. II. *Dimensions of the fire-box and boiler of some of the best engines of the Liverpool and Manchester Railway.*

It is from the dimensions we have just noticed, and more especially from those of the cylinder and stroke of the piston, that the power of locomotive engines is generally expressed. It will appear, however, in the course of this work, that for such expression of the power to be complete, and really sufficient to give the effect of the engine under all circumstances, the evaporating power of the engine, or, which amounts to the same, the heating

surface of the boiler, ought to be considered also. Without this principal element, an expression of the power of a steam engine is mere illusion.

In the fire-box and boiler resides, in fact, the real source of the effects of the engine: the cylinder and other parts are the means of transmitting and modifying the power; but what could be their use, if that power itself did not exist?

To complete, therefore, the proportions already given above, we shall add here a Table of the dimensions of the fire-box and boiler in the different engines to which we shall have occasion to refer. In another part of the work, our experiments will enable us to replace this complex datum by the simple expression of the evaporating power of those engines. The two most important columns of this Table are those which show the extent of surface exposed to the action of the caloric, whether radiating or communicative.

We introduce the engines in the order of the dates of their construction. The two engines *Goliath* and *Fire-fly* bear the number 1, because it will be seen farther on, in Chapter X., that in rebuilding those engines, boilers were adapted to them different from those which they had originally, that is to say, different from those which appear in this Table; and therefore we shall have to distinguish these new boilers by the number 11.

Dimensions of the Fire-box and Boiler of some of the best Locomotive Engines of the Liverpool and Manchester Railway.

Name of the engine.	Diameter of the cylinder.	Length of stroke of the piston.	Diameter of the boiler.	Length of the boiler and tubes.	Number of tubes.	Internal diameter of the tubes.	Area of the fire-box, or surface exposed to the radiating caloric.	Area of the tubes, or surface exposed to the contact of the flame and heated air.	Area of the fire-grate.	Quantity of fuel contained in the fire-box to the height of the lowest row of tubes.	Diameter of the chimney.
	in.	inches.	feet.	feet.		inches.	sq. feet.	sq. feet.	sq. feet.	cubic feet.	inches.
Samson	14	16	3·50	7	140	1·47	40·20	377·41	7·50	10·87	12·50
Jupiter	11	16	2·75	6·50	79	1·47	36·06	197·75	6·08	11·12	12
Goliath 1 . . .	14	16	3·50	7	132	1·47	40·31	355·84	7·50	10·87	12·50
Vulcan	11	16	3	6·50	107	1·47	34.45	267·84	6·50	7·64	13·50
Fury	11	16	3	6·50	107	1·47	32·87	267·84	6·12	8·13	13·50
Victory	11	16	3	6·75	97	1·47	37·63	252·15	6·27	11·47	13·50
Atlas	12	16	3	7·88	65	1·47	57·06	197·25	9·20	13·06	12
Vesta	$11\frac{1}{8}$	16	2·75	7	80	1·47	46	215·66	7·06	11·72	11·50
Liver	11	16	3	6·50	97 {70 27}	1·60 1·22	39·66	246·23	8·11	12·48	13·50
Ajax	11	18	2·75	6·66	63	1·85	32·64	202·77	6·08	8·32	13·50
Leeds	11	16	3	6·50	107	1·47	34·57	267·84	6·19	8·23	13·50
Fire-fly 1 . . .	11	18	3	7·50	110	1·47	43·91	317·71	7·16	14·30	13·50
Star	14	12	3·08	7·88	92	1·47	49·71	279·18	7·76	10·32	12

It will be seen hereafter, that, with a boiler of those dimensions and of such a form, the engines are able to evaporate about a cubic foot of water per minute, or a pound of water per second, at the effective pressure in the boiler of 50 lbs. on the square inch.

Sect. III. *Of the old Locomotive Engines.*

The description given above is applicable to engines intended for great speed, and particularly for the conveyance of passengers. That form is exclusively adopted in all modern railways.

On some lines, however, engines of another construction are to be found. The railway from Stockton to Darlington being used for a different service, that is to say, for the conveyance of coals and for a more moderate velocity, it may be proper to give here an idea of the engines used on that line.

Those engines are of different models, from the oldest to the most recent ones.

In some the fire passes through the boiler in a single tube, which serves as a fire-place, and communicates directly with the chimney. In some others the tube bends round in the boiler before it reaches the other end, and comes back to the chimney, which, in that case, is placed next to the door of the fire-place. In others, the tube or flue, when it reaches the end of the boiler, divides and returns towards the chimney, as two smaller tubes. In some, the fire being still placed

in an internal flue, the flame returns to the chimney by means of about 100 small brass tubes, on a principle similar to that of the Liverpool engines. Lastly, three of them are constructed on the same model as those of Liverpool.

The Company carries both passengers and goods. The first travel with a speed of twelve miles, and the second of eight miles, an hour. Of the different forms of boilers, those only with a set of small tubes suit for carrying passengers; the others cannot generate a sufficient quantity of steam for the velocity wanted. But when a speed of eight miles per hour only is required, the most convenient boilers have been found to be those with one returning tube. They generate a sufficient quantity of steam for the work required of them, and have the advantage of being cheap in regard to prime cost and repairs, as their form is simple, and they are entirely made of iron, whilst the tube boilers require the use of copper.

Besides the difference in the form of the boilers, the other parts of the engine differ also. The cylinders are placed on the outside, and in a vertical position. The motion is not communicated from the piston to the engine by a crank in the axle, but by a rod working outside of the wheel, and resting upon a pin fixed in one of the spokes. Those engines have in general six equal wheels, of four feet diameter. Two of the wheels are worked by the steam, as has been just explained; and the four

others are attached to the former by connecting-rods, which cause them to act all together.

The weight of these engines varies. Setting aside those which we have mentioned as being on the model of the Liverpool ones, and which are very light, the average weight of the others is from ten to twelve tons.

All these engines are supported on springs. In some of the older ones, the water of the boiler, pressing upon small moveable pistons, and pressed itself by the steam contained in the boiler, was intended to supersede the springs; but though that system displayed a great deal of ingenuity, the spring it formed was found in practice to be too variable, and the system was given up.

The usual proportions adopted for the engines on that railway are the following:

Cylinder	14½ inches.
Stroke	16 —
Wheels	4 feet.
Weight	11 tons.
Effective pressure	48 lbs. per square inch.

The pressure, however, varies according to the ascertained solidity of the boiler. When the sheets of which it is formed begin to grow very thin, the pressure is sometimes reduced to 36 lbs. only per square inch; in other circumstances, it is, on the contrary, increased to 60 lbs.

CHAPTER II.

OF THE LAWS WHICH REGULATE THE MECHANICAL ACTION OF THE STEAM.[1]

Sect. I. *Relation between the temperature and the pressure of the steam in contact with the liquid.*

Before entering upon considerations which have for their basis the effects of the steam, it may be necessary to lay down, in a few words, some of the laws according to which the mechanical action of the steam is determined or modified.

In the calculation of steam engines it is requisite to consider four things in the steam.

Its *pressure*, which is also called tension or elastic force, and which is the pressure it exerts on every unit of the surface of the vessel that contains it.

Its *temperature*, which is the number of degrees marked by a thermometer immerged in it.

Its *density*, which is the weight of a unit of its volume.

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[1] This chapter has already appeared in the work entitled "*Theory of the Steam Engine,*" but we deem it convenient to give the greater part of it here also, that the reader may not be obliged to recur to another work.

And its *relative volume*, which is the volume of a given weight of steam compared to the volume of the same weight of water, or, in other words, to the volume of the water that has served to produce it. We deem it necessary to add here the word *relative*, in order to avoid the confusion which would otherwise arise continually between the absolute volume filled by the steam, which may depend on the capacity of the vessel that contains it, and the relative volume which is the inverse of the density. Thus, for instance, steam generated under the pressure of the atmosphere may fill a vessel of any size, but its relative volume will always be 1700 times that of water.

When the volumes occupied by the same weight of two different steams are compared together, it is evidently a comparison of what we call the relative volumes of those two steams. For, the two steams compared having the same weight, correspond to the same volume of water evaporated. Therefore it follows that the ratio of the relative volumes of the two steams is the same as the ratio of their absolute volumes.

To make this more clear, if S express a given volume of water, M the absolute volume of the steam resulting from it under a certain pressure p, and M′ the absolute volume of the steam which results from it under another pressure p', the relative volume of the steam under the pressure p, which relative volume we will express by μ, will be

$$\mu = \frac{M}{S};$$

and the relative volume of the steam under the pressure p', which relative volume we will express by μ', will be

$$\mu' = \frac{M'}{S}.$$

Consequently will be deduced

$$\frac{\mu}{\mu'} = \frac{M}{M'};$$

that is to say, the ratio between the absolute volumes occupied by like weights of two different steams, is, as we have said, nothing more than the ratio between the relative volumes of those steams.

These definitions premised, the steam may be considered at the moment of its generation in the boiler, when still in contact with the liquid from which it emanates, or else as being separated from that liquid.

When the steam, after having been formed in a boiler, remains in contact with the generating water, it is observed that the same temperature corresponds invariably to the same *pressure*, and *vice versâ*. It is impossible then to increase its temperature, without its pressure and density increasing spontaneously at the same time; and it is impossible also to increase its density or its pressure, except by increasing at the same time its temperature. In this state the steam is therefore at its

maximum density and pressure for its temperature, and then a constant connexion visibly exists between the temperature and the pressure.

If on the contrary the steam be separated from the water that generated it, and that the temperature be then augmented, the state of maximum density will cease, since there will be no more water to furnish the surplus of steam, or increase of density, corresponding to the increase of temperature. That invariable connexion above mentioned, between the temperature and the pressure, will then no longer exist, and, by accessory means, the one may at pleasure be augmented or diminished, without any necessity of a concomitant variation taking place in the other, as it happens in the case of the maximum density.

It is necessary then to distinguish between these two states of the steam.

One of the most important laws on the properties of steam is that which serves to determine the elastic force of the steam in contact with the liquid, when the temperature under which it is generated is known; or, reciprocally, to determine that temperature when the elastic force is known. Not only is this inquiry of a direct utility, but we shall see in the sequel that it serves equally to determine the density or the relative volume of the steam formed under a given pressure, a point of knowledge indispensable in the calculation of steam engines.

Experiments on this subject had long been taken

in hand, and they were very numerous for steam formed under pressures less than that of the atmosphere; but for high temperatures, the experiments extended but to pressures of four or five atmospheres. Some few only went as far as eight, and that without completing the scale in the interval. The extreme difficulty of researches of this kind, if it be desired to attain results really exact, the heavy expenses they occasion, and the danger attending them, had prevented the experiments from being carried farther. But to the Academy of Sciences of the Institute of France we are indebted for a complete Table on this subject. The Academy confided the conduct of these delicate experiments to two distinguished scientific men, Messrs. Arago and Dulong, who evinced in them every nicety that a perfect knowledge of the laws of natural philosophy could suggest, to avoid the ordinary causes of error. Never were researches of this kind conducted on so vast a scale, nor with more accuracy. The pressure of the steam was measured by effective columns of mercury contained in tubes of crystal glass, which together extended to the height of 87 feet English. The instruments were constructed by the most skilful makers, and no expense was spared.[2]

[2] Vide Exposé des recherches faites par ordre de l'Académie des Sciences, pour déterminer les forces élastiques de la vapeur d'eau à de hautes températures. *Mémoires de l'Académie des Sciences*, tome x.; *Annales de Chimie et de Physique*, tome xliii. 1830.

Therefore the greatest degree of confidence is to be attached to their results.

These beautiful experiments furnish a complete series of observations, from the pressure of 1 atmosphere to that of 24. To form, however, a Table extending beyond this limit, Messrs. Dulong and Arago have sought to deduce from their observations a formula which might represent temperatures for still higher pressures without any noticeable error. They have in fact attained that end, by means of a formula which we shall presently report, and whose accord with experience is such, for all that part of the scale above four atmospheres, as to give room to think that, on being applied to pressures up to 50 atmospheres, the error in temperature would not in any case exceed 1 degree of the centigrade thermometer, or 1·8 degree of Fahrenheit. They were enabled then, as well from the result of their observations as by means of an amply justified formula, to compose a Table of temperatures of steam up to 50 atmospheres of pressure, with the certainty of committing no error worthy of note.

Though the formula of Messrs. Arago and Dulong may be applied to pressures comprised between 1 and 4 atmospheres, with an approximation that would suffice for most of the exigencies in the arts, they did not indicate the use of it for that interval, because in that part of the scale other formulæ already known accord more exactly with the results of observation, and ought, in consequence, to be

preferred. Among those formulæ, that originally proposed by Tredgold, and afterwards modified by his translator, M. Mellet, gave the most exact results; and no inconvenience arises from the use of it, when it is required merely to compose a Table by intervals of half-atmospheres. But as, for the more commodious use of the formulæ which we have to propose in this work, we shall want to establish a Table by intervals of pounds per square inch; we deem it better to employ a formula which we shall give with the others presently, and which, approaching as near as that of Tredgold to the results of direct observation, in the points furnished by experiment, has moreover the advantage of coinciding exactly at 4 or 4½ atmospheres with the formula of Messrs. Dulong and Arago, which is to form the continuation of it.[3]

[3] In fact, comparing, in French measure, the two formulæ with the observation, we find the following results, as it will be easy to verify hereafter.

Elastic force of the steam in atmospheres.	Observed temperature, by the centigrade thermometer.	Temperature given by Tredgold's formula, modified by Mellet.	Temperature given by the proposed formula.	Temperature given by the formula of Messrs. Arago and Dulong.
1	100	99·96	100	,,
2·14	123·7	123·54	123·34	,,
2·8705	133·3	133·54	133·17	,,
4	,,	145·43	144·88	,,
4·5735	149·7	150·39	149·79	149·77

It appears that the formula which we propose differs from the

These formulæ, as well as other similar ones, have the inconvenience of suiting only a limited part of the scale of temperatures.

Among the formulæ proposed by different authors on the same subject, that of Southern is very suitable to steam formed under pressures inferior to that of one atmosphere; it deviates then from the truth only in very low pressures, as appears from the experiments of that engineer. But for pressures superior to 1 atmosphere it ceases to have the same accuracy: from 1 to 4 atmospheres it gives, in fact, more error than that of Tredgold modified, and above 4 atmospheres the error rises rapidly to 1 and 1·5 degree of the centigrade thermometer, or 1·8 and 2·6 degrees of Fahrenheit; so that the formula of Messrs. Arago and Dulong, which is, besides, of more easy calculation, becomes then far preferable to it.

That of Tredgold modified, as well as that which we propose to substitute for it, represent very closely the observations for the interval between 1 and 4 atmospheres; but below that point they are incorrect, and above it they are inferior in point of accuracy to that of Messrs. Dulong and Arago.

The latter accords remarkably well with the facts,

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observed temperatures nearly as much as that of Tredgold modified; but as the difference from the observation is on the *minus* side instead of the *plus*, there results a coincidence at 4½ atmospheres with that of Messrs. Arago and Dulong.

from 4 atmospheres to 24. In this interval its greatest difference with observation is ·4 degree of the centigrade thermometer or ·7 of Fahrenheit, and nearly all the other differences are only ·1 degree centigrade or ·18 Fahrenheit; but, as we have already said, it begins to deviate from the observation below 4 atmospheres.

No one, then, of these formulæ suits the whole series of the scale of temperatures, and to hold exclusively to any one of them would be knowingly to introduce errors into the Tables. As, moreover, the true *theoretic* law which connects the pressures with the temperatures is unknown, and as these formulæ are mere formulæ of interpolation, established solely from their coincidence with the facts, the only right mode of making use of them is to apply each respectively to that portion of the series which it suits. Then, from the comparison of their results with experience, one may rest assured that the error on the temperature will in no point exceed seven-tenths of a degree of Fahrenheit, or four-tenths of a degree of the centigrade thermometer. This is, therefore, the means we shall adopt in the formation of the Tables we are about to present.

The formulæ, which will serve to compose these Tables, are then the following, which we present here, not in their original terms, but transformed, for greater convenience, into the measures usual in practice; that is, expressing the pressure p in pounds per square inch or in kilograms per square

centimetre, and the temperature t, in degrees of Fahrenheit's, or of the centigrade thermometer, reckoned in the ordinary manner.

Southern's formula, suitable to pressures less than that of the atmosphere (English measures):

$$p = \cdot 04948 + \left(\frac{51 \cdot 3 + t}{155 \cdot 7256}\right)^{5 \cdot 13},$$

$$t = 155 \cdot 7256 \sqrt[5 \cdot 13]{p - \cdot 04948} - 51 \cdot 3.$$

Tredgold's formula modified by M. Mellet, suitable to pressures from 1 to 4 atmospheres (English measures):

$$p = \left(\frac{103 + t}{201 \cdot 18}\right)^{6},$$

$$t = 201 \cdot 18 \sqrt[6]{p} - 103.$$

Proposed formula, suitable like the preceding, to pressures from 1 to 4 atmospheres (English measures):

$$p = \left(\frac{98 \cdot 806 + t}{198 \cdot 562}\right)^{6},$$

$$t = 198 \cdot 562 \sqrt[6]{p} - 98 \cdot 806.$$

Formula of Messrs. Dulong and Arago, suitable to pressures from 4 to 50 atmospheres (English measures):

$$p = (\cdot 26793 + \cdot 0067585\ t)^{5},$$

$$t = 147 \cdot 961 \sqrt[5]{p} - 39 \cdot 644.$$

Southern's formula, suitable to pressures less than that of the atmosphere (French measures):

$$p = \cdot 0034542 + \left(\frac{46\cdot 278 + t}{145\cdot 360}\right)^{5\cdot 13},$$

$$t = 145\cdot 360 \sqrt[5\cdot 13]{p - \cdot 0034542} - 46\cdot 278.$$

Tredgold's formula modified by M. Mellet, suitable to pressures of 1 to 4 atmospheres (French measures):

$$p = \left(\frac{75 + t}{174}\right)^6,$$

$$t = 174 \sqrt[6]{p} - 75.$$

Proposed formula, suitable like the preceding, to pressures from 1 to 4 atmospheres (French measures):

$$p = \left(\frac{72\cdot 67 + t}{171\cdot 72}\right)^6,$$

$$t = 171\cdot 72 \sqrt[6]{p} - 72\cdot 67.$$

Formula of Messrs. Dulong and Arago, suitable to pressures from 4 to 50 atmospheres (French measures):

$$p = (\cdot 28658 + \cdot 0072003\, t)^5,$$

$$t = 138\cdot 883 \sqrt[5]{p} - 39\cdot 802.$$

Besides the formulæ which we have just related, there exists another proposed by M. Biot, which, compared by that illustrious natural philosopher to the above-mentioned experiments on high pressures, to those of Taylor on pressures approaching nearer to 100 degrees centigrade, and to a numerous series of manuscript observations

made by M. Gay-Lussac, from 100° to — 20 degrees centigrade, reproduces the results observed, with very slight accidental deviations, such as the experiments themselves are liable to. This formula, which has consequently the advantage over the preceding, of being applicable to all points of the scale, is the following:—

$$\log. p = a - a_1 b_1^{20+t} - a_2 b_2^{20+t}.$$

Log. p is the tabulary logarithm of the pressure expressed in millimetres of mercury at 0° centigrade; t is the centesimal temperature counted on the air thermometer, and the quantities a, a_1, a_2, b_1, b_2, are constant quantities which have the following values:

$$a = 5{\cdot}961313330259,$$
$$\log. a_1 = \bar{1}{\cdot}82340688193,$$
$$\log. b_1 = -{\cdot}01309734295,$$
$$\log. a_2 = {\cdot}74110951837,$$
$$\log. b_2 = -{\cdot}00212510583.$$

This formula cannot fail to be extremely useful in many delicate researches on the effects of steam; but to establish, by its means, a Table of the form we require, the pressure ought first to be deduced from it for each degree of the air thermometer; then these degrees ought to be afterwards changed into degrees of the mercury thermometer; and as this would not give the temperatures corresponding to given pressures, by regular intervals, a subsequent interpolation would be still necessary to make the Table in the proper disposition. These long opera-

tions induced us to give the preference to the previously cited formulæ, for the construction of the Tables which we shall shortly present.

Sect. II. *Relation between the relative volumes and the pressures, at equal temperature, or between the relative volumes and the temperatures, at equal pressure, in the steam separated from the liquid.*

We have said that when the steam is in contact with the generating liquid, its pressure is necessarily connected with its temperature; and as the density of an elastic fluid depends only on its temperature and its pressure, it follows that the density is then always constant for a given temperature or pressure. But when the steam is separated from the liquid, that connexion between the temperature and the pressure no longer exists. The temperature of the steam may then be varied without changing its pressure, or reciprocally; and according as the one or the other of these two elements is made to vary, the density of the steam undergoes changes which have been an object of investigation among natural philosophers.

One very remarkable law in the effects of gas and steam is that which was discovered by Mariotte or Boyle, and has since been confirmed, as far as to pressures of 27 atmospheres, by Messrs. Arago and Dulong. It consists in this, that if the

volume of a given weight of gas or of steam be made to vary without changing its temperature, the elastic force of the gas will vary in the inverse ratio of the volume it is made to occupy; in other words, in direct ratio of its density. That is to say, if v and v' express the volumes occupied by the same weight of steam, and p and p' the pressures which maintain the steam compressed under those respective volumes, the temperature, moreover, being the same in both cases, the following analogy will exist:

$$\frac{p}{p'} = \frac{v'}{v}.$$

And therefore, μ and μ' being the *relative* volumes of the steam at the pressures p and p', we shall have

$$\frac{p}{p'} = \frac{\mu'}{\mu}.$$

According to this law, if a given weight of an elastic fluid be compressed to half its primitive volume, without changing its temperature, the elastic force of that fluid will become double. But it is plain that this effect cannot take place in the steam in contact with the liquid, because it supposes that during the change of pressure the temperature remains constant, whereas we have seen that in such state, the pressure always accompanies the temperature, and *vice versâ*.

Another property equally important in the ap-

preciation of the effects of steam has been discovered by a celebrated chemist of our times, M. Gay-Lussac. It consists in this, that if the temperature of a given weight of an elastic fluid be made to vary, its tension being maintained at the same degree, it will receive augmentations of volume exactly proportional to the augmentations of temperature; and, according to the latest experiments, for each degree of the centigrade thermometer, the increase of volume will be ·00364 of the volume which the same weight of fluid occupies at the temperature zero. If the temperatures are taken from Fahrenheit's thermometer, each augmentation of 1 degree in the temperature will produce an increase of ·00202 of the volume occupied by the fluid at the temperature of 32°.

If then we call V the volume of the given weight of the elastic fluid, under any pressure, and at the temperature of 32 degrees of Fahrenheit, the volume it will occupy under the same pressure, and at the temperature t of Fahrenheit, will be

$$v = V + V \times \cdot 00202\ (t - 32).$$

It follows that, between the volumes v and v' occupied by the same weight of steam, at the same pressure and under the respective temperatures t and t', there will be the following analogy:

$$\frac{v}{v'} = \frac{1 + \cdot 00202\ (t-32)}{1 + \cdot 00202\ (t'-32)}.$$

And since we have seen that the ratio between the volumes occupied by the same weight of two different steams is no other than the ratio between the relative volumes of those two steams, the two preceding analogies will also be true, when we replace the ratio of the two absolute volumes v and v', by the ratio of the *relative* volumes μ and μ' of the steam.

This law, supposing that the temperature of the steam changes, without the pressure undergoing any change, obviously cannot apply to the effects produced in steam in contact with the liquid, since in such steam the pressure changes necessarily and spontaneously with the temperature.

SECT. III. *Relation between the relative volumes, the pressures, and the temperatures, in the steam in contact or not in contact with the liquid.*

As it has just been observed, neither Boyle's law nor that of Gay-Lussac can apply alone to changes which take place in the steam remaining in contact with the liquid. But it is clear that from the two a third relation may be deduced, whereby to determine the variations of volume which take place in the steam, by virtue of a simultaneous change in the temperature and in the pressure; and this relation may then comprehend the case of the steam in contact with the

liquid, since it will suffice to introduce into the formulæ the pressures and temperatures which, in this state of the steam, correspond to each other.

Suppose then it be required to know the volume occupied by a given weight of steam, which passes from the pressure p' and temperature t', to the pressure p and temperature t. It may be supposed that the steam passes first from the pressure p' to the pressure p without changing its temperature, which, from Boyle's law, will give between the relative volumes of the steam the analogy

$$\mu''=\mu'\frac{p'}{p};$$

then supposing this steam to pass from the temperature t' to the temperature t, without changing its pressure, the relative volume of the steam, according to the law of Gay-Lussac, will become

$$\mu=\mu''\frac{1+\cdot00202\ (t-32)}{1+\cdot00202\ (t'-32)}=$$

$$=\mu'\frac{p'}{p}.\frac{1+\cdot00202\ (t-32)}{1+\cdot00202\ (t'-32)}.$$

This formula will then express the law according to which the relative volume of the steam changes, by virtue of a given combination of pressure and temperature. Consequently, substituting in this equation for p and t, p' and t', the pressures and temperatures only which correspond to each other

in the steam in contact with the liquid, we shall have the analogous changes which take place in the relative volume of the steam, when it is not separated from the water which generated it.

On the other hand, it is known by experience, that under the atmospheric pressure, or 14·706 lbs. per square inch, and at the temperature of 212° of Fahrenheit's thermometer, the relative volume of the steam in contact with the liquid is 1700 times that of the water which has produced it. Hence it is easy to conclude the relative volume of the steam at any given pressure p and at the corresponding temperature t. It suffices, in fact, to insert the above values for p', t', and μ', in the general equation obtained above, and the result will be

$$\mu = 1700 \times \frac{14 \cdot 706}{p} \times \frac{1 + \cdot 00202\ (t-32)}{1 + \cdot 00202 \times 180} =$$

$$= 18329\ \frac{1 + \cdot 00202\ (t-32)}{p}.$$

Thus we may, by means of this formula, calculate the relative volume of the steam generated under a given pressure, as soon as we know the temperature answering to that pressure in steam at the maximum of density for its temperature.

It is what we have done in the construction of the following Table. The second column has been

formed by calculating the temperature of the steam at the maximum density, from the formulæ which we have given in the first section of this chapter. Then using this series of temperatures in the formula which precedes, we have concluded the third column, or the relative volumes of the steam in contact with the liquid, under all the pressures comprised between 1 and 8 atmospheres. This Table will, in consequence, dispense with all calculation with regard either to the research of the temperatures, or to that of the relative volumes of the steam; and its extent will suffice for all applications that occur in the working of steam engines.

When we speak of steam *generated* under a given pressure, we understand the steam considered at the moment of its generation, and consequently still in contact with the liquid. We have explained elsewhere that the volume of the steam, compared to that of the water which has produced it, is precisely what we call the *relative* volume of the steam.

Table of the temperature and volume of the steam generated under different pressures, compared to the volume of the water that has produced it.

Total pressure, in English pounds per square inch.	Corresponding temperature, by Fahrenheit's thermometer.	Relative volume, or volume of the steam compared to the volume of the water that has produced it.	Total pressure, in English pounds per square inch.	Corresponding temperature, by Fahrenheit's thermometer.	Relative volume, or volume of the steam compared to the volume of the water that has produced it.
1	102·9	20954	37	263·7	727
2	126·1	10907	38	265·3	710
3	141·0	7455	39	266·9	693
4	152·3	5695	40	268·4	677
5	161·4	4624	41	269·9	662
6	169·2	3901	42	271·4	647
7	176·0	3380	43	272·9	634
8	182·0	2985	44	274·3	620
9	187·4	2676	45	275·7	608
10	192·4	2427	46	277·1	596
11	197·0	2222	47	278·4	584
12	201·3	2050	48	279·7	573
13	205·3	1903	49	281·0	562
14	209·0	1777	50	282·3	552
15	213·0	1669	51	283·6	542
16	216·4	1572	52	284·8	532
17	219·6	1487	53	286·0	523
18	222·6	1410	54	287·2	514
19	225·6	1342	55	288·4	506
20	228·3	1280	56	289·6	498
21	231·0	1224	57	290·7	490
22	233·6	1172	58	291·9	482
23	236·1	1125	59	293·0	474
24	238·4	1082	60	294·1	467
25	240·7	1042	61	294·9	460
26	243·0	1005	62	295·9	453
27	245·1	971	63	297·0	447
28	247·2	939	64	298·1	440
29	249·2	909	65	299·1	434
30	251·2	882	66	300·1	428
31	253·1	855	67	301·2	422
32	255·0	831	68	302·2	417
33	256·8	808	69	303·2	411
34	258·6	786	70	304·2	406
35	260·3	765	71	305·1	401
36	262·0	746	72	306·1	396

Total pressure, in English pounds per square inch.	Corresponding temperature, by Fahrenheit's thermometer.	Relative volume, or volume of the steam compared to the volume of the water that has produced it.	Total pressure, in English pounds per square inch.	Corresponding temperature, by Fahrenheit's thermometer.	Relative volume, or volume of the steam compared to the volume of the water that has produced it.
73	307·1	391	92	323·5	317
74	308·0	386	93	324·3	313
75	308·9	381	94	325·0	310
76	309·9	377	95	325·8	307
77	310·8	372	96	326·6	305
78	311·7	368	97	327·3	302
79	312·6	364	98	328·1	299
80	313·5	359	99	328·8	296
81	314·3	355	100	329·6	293
82	315·2	351	105	333·2	281
83	316·1	348	120	343·3	249
84	316·9	344	135	352·4	224
85	317·8	340	150	360·8	203
86	318·6	337	165	368·5	187
87	319·4	333	180	375·6	173
88	320·3	330	195	382·3	161
89	321·1	326	210	388·6	150
90	321·9	323	225	394·6	141
91	322·7	320	240	400·2	133

SECT. IV. *Direct relation between the relative volumes and the pressures, in the steam in contact with the liquid.*

It has just been seen, from the formulæ given in the preceding section, that the density and the relative volume of the steam, whether separated from the liquid or not, are deduced from the knowledge of the simultaneous pressure and temperature. It is likewise known that in the steam in contact

with the liquid the temperature depends immediately on the pressure. It should therefore be possible to find a relation proper to determine directly the relative volume of the steam in contact with the liquid, or, in other words, of the steam at the maximum density and pressure for its temperature, by means of the sole knowledge of the pressure under which it is formed.

The equation which gives the relative volume of the steam in any state whatever, in terms of its pressure and temperature, has been given above. We have also shown the formulæ which serve to find the temperature in terms of the pressure, in steam in contact with the liquid. Eliminating then the temperature from the equation of the volumes and that of the temperatures, we shall obtain definitively the relation sought, or the relative volume of the steam at the maximum density, in terms of the pressure only.

But here starts the difficulty. First, M. Biot's formula not being soluble with reference to the temperature, does not admit the necessary elimination. In the next place, the assemblage of the three formulæ presented above, which are made to succeed each other, suit very well in the formation of tables of correspondence between the pressures and the temperatures, when that is the end proposed. Likewise, in an inquiry relative to the expansion of the steam in an engine, when it is known precisely within what limits of pressure

that expansion will take place, it may immediately be discerned which of the three formulæ is applicable to the case to be considered, and then t may be eliminated between that formula and the equation of volumes. But if the question regards, for instance, the case wherein the steam generated in the boiler under a pressure of 8 or 10 atmospheres might, according to the circumstances of the motion, expand during its action in the engine, either to a pressure less than 1 atmosphere, or to a pressure between 1 and 4 atmospheres, or, in fine, to a pressure superior to 4 atmospheres; then we shall not know which of the three formulæ to use in the elimination, and it will be impossible to arrive at a general equation representing the effect of the engine in all cases.

Besides, were we even to adopt any one of those equations, the radicals they contain would render the calculation so complicated as to make it unfit for practical applications.

The equations of temperature hitherto known cannot then solve the question that presents itself, that is to say, satisfy the wants of the calculation of steam engines in this respect; and, consequently, the only means left is to seek, in a direct manner, an approximate relation, proper to give immediately the relative volume of the steam at the maximum density in terms of the pressure alone.

With this view M. Navier had proposed the expression:

$$\mu = \frac{1000}{\cdot09 + \cdot0000484\, p},$$

in which μ is the *relative* volume, or the ratio of the volume of the steam to that occupied by the same weight of water, and p the pressure expressed in kilograms per square metre.

It would be easy to transform this formula into English measures; but as it deviates considerably from experience for pressures below the atmosphere, and therefore was never intended to apply to condensing engines; and as, moreover, for non-condensing or high pressure engines, it is not nearly so exact as the formula which we are going to propose, we shall only present here the last one in English measures.

Formula for high pressure engines:

$$\mu = \frac{10000}{1{\cdot}421 + \cdot0023\, p}.$$

In this expression μ represents the relative volume of the steam, and p is its pressure expressed in lbs. per square foot.

To give a precise idea of the approximation given by this formula, we here subjoin a Table of the values it furnishes for the principal points of the scale of pressures. It will be remarked that in high pressure engines, the steam can hardly be spent at a *total* pressure less than two atmospheres, by reason of the atmospheric pressure, the friction of the engine, and the resistance of the load. Therefore

it is needless to require of the formula exact volumes for pressures less than two atmospheres.

Relative volume of the steam generated under different pressures, calculated by the proposed formula.

Total pressure of the steam, in pounds per square inch.	Volume of the steam, calculated by the ordinary formulæ.	Volume calculated by the proposed formula for high-pressure non-condensing engines.
15	1669	,,
20	1280	1243
25	1042	1031
30	882	881
35	765	768
40	677	682
45	608	613
50	552	556
55	506	509
60	467	470
65	434	436
70	406	406
75	381	381
80	359	358
85	340	338
90	323	320
105	281	276
120	249	243
135	224	217
150	203	196

Sect. V. *Of the constituent heat of the steam in contact with the liquid.*

There is yet an inquiry, relative to the properties of steam, which has long fixed the attention of natural philosophers: it is that of the quantity of heat necessary to constitute the steam in the state

of an elastic fluid under various degrees of elasticity.

It is well known that when water is evaporated under the atmospheric pressure, in vain new quantities of heat may be added by means of the furnace; neither the temperature of the water, nor that of the steam, ever rise above 100° of the centigrade thermometer, or 212° of Fahrenheit. All the heat then which is incessantly added to the liquid must pass into the steam, but must subsist there in a certain state which is called *latent*, because the heat, though really transmitted by the fire, remains nevertheless without any effect upon the thermometer, nor does it afterwards become perceptible till the moment of disengaging itself, on the steam being condensed.

This latent heat evidently serves to maintain the molecules of water in the degree of separation suitable to their new state of elastic fluid; and it is then absorbed by the steam, in a manner similar to that which is absorbed by the water, on passing from the solid state, or state of ice, to the liquid. But it is important to know the quantity of the latent heat, in order to appreciate with accuracy the modifications the steam may undergo.

Some essays made by Watt had already elicited that the steam, at the moment of its generation, or in contact with the liquid, contains the same quantity of total heat, at whatever degree of tension, or, in other words, at whatever degree of density,

it may be formed. The experiments of Messrs. Sharpe and Clement have since confirmed this result. From them is deduced, that the quantity of latent heat contained in the steam in contact with the liquid is less and less, in proportion as the temperature is higher; so that the total heat, or the sum of the latent heat plus the heat indicated by the thermometer, forms in all cases a constant quantity represented by 650° of the centigrade thermometer, or, 1170° of Fahrenheit's.

Southern, on the contrary, has concluded from some experiments on the pressure and temperature of steam, that it is the latent heat which is constant; and that, to have the total quantity of heat actually contained in steam formed at a given temperature, that temperature must be augmented by a constant number, representing the latent heat absorbed by the steam in its change of state.

Some authors have deemed this opinion more rational, but the observations we are about to relate seem to us to set the former beyond all doubt.

It is known, that when an elastic fluid dilates itself into a larger space, the dilatation is invariably attended with a diminution of temperature. If, then, the former of the two laws be exact, it follows that the steam, once formed at a certain pressure, may be separated from the liquid, and provided it lose no portion of its primitive caloric,

by any external agent, it may dilate into greater and greater space, passing at the same time to lower and lower temperatures, without ceasing on that account to remain at the maximum density for its actual temperature. In effect, since we suppose that the steam has in reality lost no portion of its total heat, the consequence is, that it always contains precisely as much as suffices to constitute it in the state of maximum density, as well at the new temperature as at the former.

If, on the contrary, Southern's law be exact, when the steam, once separated from the liquid, will diminish in density as it dilates into a larger space, it will not remain at the maximum density for the new temperature. To admit indeed that it would do so, would be to verify Watt's law, since the new steam would be at the maximum density, although containing precisely the same quantity of total heat as the old. But since we admit, on the contrary, that the primitive steam contained more heat than was necessary to constitute the new at the maximum density, it follows that the surplus heat, now liberated, will diffuse itself in the new steam; and as this is separated from the liquid, the increase of heat cannot have the effect of increasing the density of the steam, but will be altogether sensible in the temperature. Thus the result will be, a steam at a certain density, indicated by the spaces into which it is dilated, and

at a temperature higher than what is suitable to that density, in steams at the maximum of density for their temperature.

Now, in a numerous series of experiments, of which we shall speak hereafter, we have found that in an engine whose steam-pipes were completely protected against all external refrigeration, the steam was generated at a very high pressure in the boiler; and, after having terminated its action in the engine, escaped into the atmosphere at pressures very low and very varied; and that in every case the steam issued forth precisely in the state of steam at the maximum of density for its temperature. Southern's law then is inadmissible, unless any one choose to suppose that in these varied changes of pressure the steam lost, by contact with the very same external surfaces, always precisely and strictly just that quantity of heat, sometimes very considerable, at other times very small, by which its temperature should have increased. Consequently the law of Watt is the only one supported by the facts.

The total quantity of heat contained in the steam in contact with the liquid, and under any pressure whatever, is then a constant quantity; and according as the sensible heat increases, the latent heat diminishes in an equal quantity.

On the other hand, according to the same law, if we conceive water to be enclosed in a vessel capable of sufficient resistance, and submitted to

temperatures of greater and greater intensity; the latent heat of the steam thence arising will be less and less as the sensible heat or temperature shall become greater; and as soon as the steam shall be generated at a temperature equal to 650° centigrade or 1170° of Fahrenheit, it will cease to absorb heat in a latent state, and will no longer receive any portion of it, but which will be sensible on the thermometer. We must then conclude that at this point the steam will have a density equal to that of water; since in passing from one state to another, it requires no farther increase of caloric, as would be necessary if any farther increase of severance were to take place between the molecules. Thus the water, though still contained in the vessel, will all have passed into the state of steam, so that there will be no more steam in contact with the liquid. From this moment, then, new quantities of heat may be applied to the vessel; but instead of acting on a liquid, which passes to the state of gas, by absorbing latent heat, it will now only act on an elastic fluid, and therefore all the increase of heat will, as in all gases, become sensible on the thermometer.

This observation explains the difficulty which would otherwise present itself; viz., that beyond 650° centigrade or 1170° of Fahrenheit, the preceding law could not subsist without the latent heat becoming a negative quantity, which is impossible.

Sect. VI.—*Of the conservation of the maximum density of the steam for its temperature, during its action in the engine.*

When an engine is at work, the steam is generated in the boiler at a certain pressure; from thence it passes into the cylinder, assuming a different pressure, and then, if it be an expansive engine, the steam, after its separation from that of the boiler, continues to dilate itself more and more in the cylinder, till the end of the stroke of the piston. It is commonly supposed that, during all the changes of pressure which the steam may undergo, its temperature remains the same, and the consequent conclusion is that, during the action of the steam in the engine, its density or relative volume follows the law of Boyle or Mariotte; that is to say, the relative volume varies in the inverse ratio of the pressure. This supposition simplifies indeed the formulæ considerably, but we shall presently see that it is contrary to experience; and therefore it becomes necessary to seek what is the true law, according to which the steam changes temperature in the engine, at the same time that its pressure changes. And as calculations relative to the effects of steam depend essentially on the volume it occupies, we must seek also what changes that volume undergoes, by reason of the variations of temperature and pressure which take place in the steam during its action.

We shall then substitute for the relation precedently indicated, according to Mariotte's law, another more real, and, what is essentially necessary to calculate the effects of steam with accuracy, deduced from the facts themselves.

We have just said that the calculations relative to steam engines suppose the steam to preserve invariably its original temperature, which allows the application of Boyle's or Mariotte's law to all the changes of density or of pressure it may undergo. However, as it is known that elastic fluids never dilate without cooling in some degree, this supposition obviously could not be realized, but on condition that the steam have time to recover from the bodies with which it is in contact, supposed to be sufficiently heated, the quantity of caloric necessary to restore its temperature, after expansion, to the same degree at which it was before. Now, the rapidity of the motion of the steam in the cylinders and the pipes, and the natural temperature of those pipes, which makes them rather liable to take caloric from the steam than to supply it with caloric, will not suffer the admission of such an hypothesis.

To obtain satisfaction on this head, in a numerous series of experiments, we adapted to the boiler of a locomotive engine a thermometer and an air-gauge or manometer; we applied also two similar instruments to the pipe through which the steam, after having terminated its action in the engine, escaped

into the atmosphere; and we observed their simultaneous indications. The steam was generated in the boiler at a total pressure varying from 40 lbs. to 65 lbs. per square inch, and escaped into the atmosphere at a pressure varying, according to different circumstances, from 20 lbs. to 15 lbs. per square inch. Had the steam preserved its temperature during its action in the engine, it would have issued forth with the pressure, for instance, of 15 lbs. per square inch, but with the temperature proper to the pressure at which it had been formed, that is, 65 lbs. per square inch. Now, nothing like this took place: during some hundreds of experiments wherein we observed and registered these effects, we found invariably that the steam escaped precisely with the temperature suitable to its actual pressure.

In effect, the divisions of the thermometer employed indicated the pressure in steam in contact with the liquid; that is to say, the degrees of temperature having been first marked in the ordinary way, the temperatures had been afterwards replaced, from known Tables, by the corresponding pressures in steam at the maximum of pressure or of density for its temperature. This instrument showed then at every moment the *maximum* pressure corresponding to the actual temperature of the steam. On the other hand, the air-gauge measured directly the real pressure of the steam. The two instruments then could agree only so long as the real pressure of the steam was at the same time the

maximum pressure corresponding to the temperature of that steam. But, during the whole course of the experiments, the thermometer was found to give identically the same degree of pressure as the air-gauge, and it equally agreed with a siphon-manometer which we had superadded to the apparatus at the point of the outlet of the steam. The steam then was generated in the boiler at a certain very high pressure, and quitted the engine at a very low one; but, on its leaving the engine, as well as at the moment of its production, that steam was at the maximum of pressure or of density for its temperature, that is to say, it was precisely in the same state in which it would have been, had it risen immediately from the liquid at its actual pressure.

We will not relate all the experiments in which we have observed this result, since it would be a mere repetition of the same thing, and since, in order at the same time to attain other determinations relative to the engine, and particularly that of the pressure due to the blast-pipe, as will hereafter appear, we necessarily made a very great number of observations on the subject; but to give an idea at least of the results, we will present a few series of them in the following Table:

Experiments on the changes of pressure and temperature of the steam, during its action in the engine.

Total pressure of the steam, in lbs. per sq. inch, at the moment of its generation in the boiler, by the air-gauge and by the thermometer.	Corresponding temperature, in degrees of Fahrenheit's thermometer.	Total pressure of the steam, in lbs. per sq. inch, at the moment of its leaving the engine,		Corresponding temperature, in degrees of Fahrenheit's thermometer.
		by the air-gauge.	by the thermometer.	
59	293	16·5	16·5	218
60	294·1	16·5	16·5	218
61	294·9	16·5	16·5	218
63	297	16·5	16·5	218
62	295·9	17·5	17·5	221·1
61	294·9	18·5	18·5	224·1
61	294·9	19·5	19·5	226·9
59	293	19·5	19·5	226·9
59	293	20·25	20·25	229
59	293	20·5	20·5	229·6
59	293	20·25	20·25	229
46	277·1	18	18	222·6
49	281	18·5	18·5	224·1
54	287·2	20	20	228·3
56	289·6	21	21	231
51	283·6	21·5	21·5	232·3
51	283·6	21·25	21·25	231·6
53	286	20·5	20·5	229·6
52	284·8	19	19	225·6
51	283·6	19	19	225·6
52	284·8	19	19	225·6
51	283·6	19	19	225·6
51	283·6	18·5	18·5	224·1
53	286	18·5	18·5	224·1
54	287·2	18·5	18·5	224·1
57	290·7	18·5	18·5	224·1
58	291·9	18·5	18·5	224·1
62	295·9	17·25	17·25	220·3
64	298·1	17·75	17·75	221·8
62	295·9	18	18	222·6
61	294·9	18·75	18·75	224·8
64	298·1	21·5	21·5	232·3
60	294·1	21·5	21·5	232·3
60	294·1	20·75	20·75	230·3
61	294·9	20·75	20·75	230·3
62	295·9	21·25	21·25	231·6
63	297	21·75	21·75	232·9

We see from these experiments, that the steam, after having been generated in the boiler at a very high pressure and temperature, lowered its pressure more or less in the engine, but that its temperature lowered at the same time, and in such sort that the steam was always at the maximum of pressure or of density for its temperature.

In the engine submitted to experiment, the steam, throughout its action, was completely protected against all external refrigeration; for the pipe which conducted it from the boiler to the cylinder was immerged into the steam of the boiler itself, as far as the point where it entered the smoke-box. Then, as well in the interval which separates that point from the entrance of the cylinder as during its action in the cylinder itself, and from its quitting the cylinder to the orifice of the blast-pipe, the steam was continually traversing passages entirely enclosed in the smoke-box, and consequently in immediate contact with the flame and hot air proceeding from the furnace. The steam could not then be liable to any external refrigeration.

The above-mentioned experiments referred then to an engine perfectly guarded against any external refrigeration. On the other hand, supposing an engine wherein these external causes of refrigeration were not provided against, the effect will be first to operate the condensation of a part of the steam produced, and there will consequently exist in the

passages traversed by the steam a certain quantity of water in its liquid state. It will be precisely the same in the cylinder of a condensing engine, after the imperfect condensation of the steam. In each of these two cases, the remaining steam will be found materially in presence of the liquid, and consequently will again be necessarily at the maximum of density for its temperature.

Finally, a third case might be supposed, that in which the steam should, on the contrary, acquire heat after its separation from the water of the boiler. Then, contrary to what has been seen to take place in the locomotive engine mentioned above, it is plain that the steam would acquire a temperature above that which is proper to steam at the maximum density for its temperature; but this case does not occur in steam engines, and it will therefore be useless to dwell on it.

It is consequently to be concluded from the foregoing, that in steam engines more or less perfectly guarded against all external refrigeration, the steam remains always, during its action in the engine, in the state of maximum density for its temperature, as if it had never ceased to be in contact with the generative liquid.

Now, we have shown in the fourth section of this chapter, that, with regard to steam in contact with the liquid, the *relative* volume may be expressed in terms of the pressure by a very simple formula, which we may present generally under the form

$$\mu=\frac{1}{n+qp}. \quad . \quad . \quad . \quad . \quad (a)$$

This analogy, in which n and q will have the numerical values already indicated, will then be applicable to all the changes of volume of the steam during its action in the engine.

From this equation, if we suppose that a certain volume of water, represented by S, be transformed into steam at the pressure p, and that we call M the *absolute* volume of steam which will be produced by it, we shall have

$$\mu=\frac{M}{S}=\frac{1}{n+qp}.$$

If afterwards the same volume of water be transformed into steam at the pressure p', and that we call M′ the *absolute* volume of the resulting steam, we shall have also

$$\frac{M'}{S}=\frac{1}{n+qp'}.$$

Consequently, between the *absolute* volumes of steam which correspond to the same weight of water, we shall have the definitive relation,

$$\frac{M}{M'}=\frac{\frac{n}{q}+p'}{\frac{n}{q}+p}; \quad . \quad . \quad . \quad . \quad (b)$$

that is to say: the volumes of the steam will be, not in the inverse ratio of the pressures, as was supposed in admitting Boyle's or Mariotte's law,

but in the inverse ratio of the pressures augmented by a constant quantity.

From the equation (b) is likewise drawn the analogy

$$p = \frac{M'}{M}\left(\frac{n}{q} + p'\right) - \frac{n}{q}. \quad . \quad . \quad . \quad . \quad (c)$$

And the two equations (b) and (c) will serve to determine, either M, or p, according to the one of these two quantities, which will be unknown.

As, in all calculations relative to the effects of steam engines, the volume occupied by a given weight of steam forms the important element of the calculation, it is very obvious that the use of the principle of the *conservation of the maximum density of the steam for its temperature*, during its action in the engine, and the formulæ by which we have represented it, will tend to the avoiding of many considerable errors in the results.

If we consider a condensing engine in which the steam generated at the pressure of 8 atmospheres, or 120 lbs. per square inch, shall expand to 10 lbs. per square inch; then, in the usual mode of calculation, it will be supposed that the steam, during its expansion, will preserve its temperature, and that its volume will vary in the inverse ratio of the pressures. The volume of the steam at the pressure of 120 lbs. per square inch is 249 times that of the water which produced it. If its temperature remained unchanged during its action in the engine, its volume after the expansion would become

$$249 \times \frac{120}{10} = 2988.$$

The supposition, then, amounts to admitting that under the pressure of 10 lbs. per square inch, the volume of the steam would be 2988 times that of the water. Now, from accurate Tables, this volume is 2427. An error, then, is induced of $\frac{1}{5}$ on the real volume of the steam, that is to say, on the effect of the engine; and this error will be almost entirely avoided by the use of our formula suitable to condensing engines (*Theory of the Steam Engine*, chap. II. sect. iv.), since it gives in this case 2417, instead of 2427, that is to say, it differs inconsiderably from the true volume of the steam.

In non-condensing engines, the error which results from the application of Mariotte's law is again very sensible, though less considerable than in the preceding engines. If, in fact, we suppose an engine wherein the steam be generated at the pressure of 5 atmospheres, or 75 lbs. per square inch, and expended at the pressure of 30 lbs. per square inch, or about 2 atmospheres, as the volume of the steam formed under the pressure of 75 lbs. per square inch is 381 times the volume of the water, it is plain that, if the action of the steam took place without the temperature changing, its volume, at the moment of its action, would be represented by the number

$$381 \times \tfrac{5}{2} = 952.$$

But from exact Tables, the volume of the steam formed at the pressure of 30 lbs. per square inch is

really 882 times the volume of the water. Admitting, by the fact, the former number instead of the latter, an error will be committed of about $\frac{1}{12}$ on the real volume of the steam, and consequently on the effect of the engine; and that error will be totally avoided by using the Tables which we have given of the volume of the steam. Using our formulæ for non-condensing engines, the resulting number for the volume of the steam will be 881 instead of 882. In this case also will thus be avoided the above-mentioned error.

We must however add, that with respect to slight differences of pressure, such as occur in a great number of cases, the error resulting from the use of Mariotte's law may become quite unnoticeable.

CHAPTER III.

OF THE PRESSURE OF THE STEAM, IN LOCOMOTIVE ENGINES.

ARTICLE I.

OF THE SAFETY-VALVES.

SECT. I. *Of the Pressure calculated according to the Levers and the Spring-balance.*

WHEN an elastic fluid is confined in a closed vessel, it produces in every direction, on the sides of the vessel, a pressure, which is the result of its elastic force, and which gives the exact measure of that force. If, the vessel being already filled with steam, a fresh quantity is continually added, the elastic force of the steam will augment more and more, and consequently also the pressure it produces on every square inch of the surface of the vessel. Now if at one point of the vessel there be a valve, that is to say, an aperture, closed with a moveable piece supporting a certain weight, it is clear that, as soon as the steam contained in the vessel produces upon the moveable plate a pressure equal to that of the weight which holds it down in the opposite

direction, the plate will begin to be lifted up; the passage will then be opened, and the steam escaping through the aperture, will show that its pressure was greater than the weight that loaded the plate or valve.

It must however be observed, that the resistance which opposes the egress of the steam does not consist only in the weight that has been placed on the valve. Besides that weight, the atmosphere produces also on the valve a certain pressure, as well as upon every other body with which it comes in contact. That pressure is known to be equal to 14·7 lbs. per square inch. It is therefore the weight, added to the pressure of the atmosphere, that gives the real measure of the elastic force of the steam; while the weight alone represents only the surplus of the pressure over the atmospheric pressure, or what is called the *effective* pressure of the steam. Consequently, when a valve has a surface of five square inches, and supports a weight of 250 lbs., which, divided between the five square inches, gives a resistance of 50 lbs. per inch, that amount of 50 lbs. expresses the *effective* pressure of the steam, a valuation frequently made use of on account of its convenience for calculation, whereas 64·7 lbs. is the real resistance opposed, and therefore the real pressure of the steam.

On this principle are grounded the means of measuring the pressure in steam engines, but instead of imposing directly a weight on the valve,

which weight must needs be considerable, a lever is used; and as moreover a heavy body suspended at the extremity of such lever would be liable to continual jerking, during the motion of the engine, which would cause an incessant opening and shutting of the valve, this weight is replaced by an equivalent spring.

Figure 16 represents the apparatus used in locomotive engines. The point C is a fixed pivot round which the lever CB may move up and down. At the point A this lever presses on the valve S by means of a pin, and is held at its extremity B by the above-mentioned spring. This consists of a spiral, which by being more or less compressed, is able to support in equilibrium, and consequently to represent, larger or smaller weights. In other words, it is a spring-balance, such as is used for weighing in daily occurrences.

This balance consists of a rod T (fig. 16) which is held in the hand, and to which is fastened a plate with a narrow oblong aperture in it. Behind this plate, and in a cylindrical tube, is a spring, the foot of which rests on the basis L, which is fixed to the plate. At its other end, this same spring is pressed by a moveable transverse bar *mn*. At the inferior part of the apparatus is a rod P, to which are fastened the objects that are to be weighed. The prolongation of the bar *mn* projects through the aperture of the plate, and is terminated by an index which appears on the outside, and which slides up and down the aperture in

proportion as the spring is more or less compressed. Divisions are engraved along that same aperture. In order to mark them, known weights of 1 lb., 2 lbs., &c. are successively suspended at P, and according as those weights, by pressing on the spring, cause the index to rise, the corresponding divisions are marked. The consequence of this is, that when an object of unknown weight is suspended at P, and makes the index rise to the point marked 10, that is to say, to the same point to which a known weight of 10 lbs. made it rise, we conclude that the object also weighs 10 lbs. This is the sort of balance which is used for measuring the pressure in locomotive engines. We see that, by taking it off from the engine, and suspending known weights to it, the divisions may easily be verified, after the balance is graduated.

On the engine, the foot P of the balance, where the object to be weighed would be suspended, is fixed in a solid manner to the boiler; and the rod T, which would be held in the hand in common weighing, is fastened to the end of the lever. This rod passes through an aperture cut through the end of the lever, and is fixed above it by a screw which rests upon the lever. When it is required that this balance shall produce a pressure of 10 lbs., nothing more is necessary than to lower the screw until the spring rises to the point marking 10 lbs., and the same for any other weight.

Vice versâ, the steam being in the boiler at an unknown degree of pressure, if we loosen gradually

the screw until the steam begins to raise the valve, that is to say, until its pressure stands in equilibrio with the pressure of the spring, the pressure of the steam will be known, for the degree then marked by the index will show the weight which is equal to it.

Knowing the weight marked on the balance, or represented by the tension of the spring, it is easy to deduce the resulting pressure on the valve per unit of surface; for the weight multiplied by the proportion of the two arms of the lever gives, firstly, the total pressure on the whole valve, and this divided by the area of the valve gives the pressure acting on each unit of its surface. Thus P being the weight inscribed on the balance, its effect on the point A will be

$$P \times \frac{BC}{AC};$$

and if the area of the valve be expressed by a, the pressure on the unit of surface will be

$$p = \frac{P \times \frac{BC}{AC}}{a}.$$

To avoid all necessity of calculation in this respect, the lever is often so constructed that the ratio of its two parts is expressed by the number itself which expresses the surface of the valve. That is, if the area of the valve is 5 square inches, the levers will be made in the proportion of 5 to 1; then the pres-

sure per unit of surface of the valve is immediately given by the weight inscribed on the balance.

If, for instance, we suppose a valve of 2½ inches in diameter, which makes very nearly 5 square inches of surface, and that the two levers BC and AC be 15 inches and 3 inches, a weight of 50 ℔s. marked on the balance will, from the ratio of the levers, act on the valve with a pressure of 5 times 50 ℔s., or 250 ℔s., which, divided among the 5 square inches of surface of the valve, will give 50 ℔s. per square inch, which is precisely the weight marked on the balance.

Sect. II. *Of the corrections to be made to the weight marked by the Spring-balance.*

The calculation explained above gives the pressure acting on the valve. However, it will easily be conceived, by the manner in which the spring-balance acts upon the valve, that, to know the pressure which really opposes the egress of the steam, it is not sufficient to read the degree where the index stops, and to calculate the effect produced at the end of the lever, as we have done above. In fact, first, besides the weight represented by the spring, and which would be suspended at the end of the lever, it is clear that the weight of the lever itself causes a certain degree of pressure; for before the steam is able to act on the spring, it must raise the whole weight of the lever. The same takes place in regard

to the disk of the valve, which must be raised before the steam can have any action on the balance.—2. When any object is weighed with the hand, that object is suspended at the lower part of the balance, but then the hand supports the upper part, that is to say, the rod, with the spring to which it is fastened; and that effort is not taken into account, because it does not make a part of the weight. Here, on the contrary, the rod, the screw, and the spring, are an additional weight really suspended at the end of the lever, over and above the pressure marked by the spring; they must all be raised before the spring can be pressed upon in any way, and can register any effort; they must therefore be taken into account. The true pressure which takes place on the valve will consequently not be known, until are added to the weight marked in the balance: 1. The pressure produced by the weight of the lever at the place of the valve; 2. The pressure produced at the end of the lever by the weight of the rod and spring of the balance.

To measure at once these two additional resistances, the following means may be used. First loosen completely the screw of the balance, till the spring no longer pulls on the lever, and till the valve bears no other weight than that of the lever itself, and its dependent apparatus. Then pass a string round the pivot A which rests on the valve, and having attached the extremities of this string to another spring-balance, raise the whole with the

hand, by means of this second balance, till you see the index of the balance of the engine stop at zero of weight. The additional weight sought will be indicated on the balance borne in the hand. It is in fact clear that, by this proceeding, all the additional weight on the valve is held in equilibrio, and that if the valve could be maintained in this state while at work, every pound of pressure in the boiler would immediately mark one pound of pressure on the balance, since there would no longer be any additional weight to raise.

By this means, then, may be known the addition that ought to be made to the pressure indicated by the balance. It is found that, when the levers are 36 inches in total length, of a usual thickness and with the balance commonly adapted to them, they produce on the valves an additional pressure of 7 to 8 ℔s. per square inch, and when they are 15 inches in total length with their corresponding apparatus, the additional pressure still amounts to 3 or 4 ℔s. per square inch. This therefore is obviously a correction not to be neglected, if in the calculation a certain degree of accuracy be required.

Finally, there is another cause of error which it is proper to note here.

In order that the valves may exactly close the opening to which they are applied, without being subject to contract an adhesion with the seat that supports them, it is necessary to make them slightly conical, or at least with a slanting border, as repre-

sented in figs. 20 and 22. When these valves rest upon and completely fill their seat, it is very clear that the steam can only act upon their inferior surface; consequently, the area which we have expressed above by *a*, must be taken after the *inferior* diameter of the valve. To be perfectly exact, this area ought even to be taken from the diameter of the orifice covered by the valve, for the latter might be constructed in the form of fig. 21, where it is seen that the surface according to which the pressure is to be divided, is not *ab* but *cd*. Taking then the proper measurements, and calculating as we have done above, the exact pressure will be found for every case in which the valve rested upon the seat, or, if raised, was raised only for an instant, and in a very small degree; but whenever the steam, being generated in greater quantity than it is expended by the cylinders, escapes with force through the valve, it raises considerably the disk of the valve: the consequence then is, that, instead of acting merely on the inferior surface of the valve, it evidently acts on a greater surface, and which is still greater the more the valve is raised.

The effect of this alteration in the diameter of the valve, which at first sight appears trifling, is in fact very considerable. Let us suppose, for instance, that we have a valve of 2·50 inches in diameter at the bottom, and 3 inches at the top. Let us further suppose that, by the effect of the blowing of the steam, the valve has been raised so as to

have increased its real diameter only by one-eighth of an inch; the surface of the valve, which was at first

$$4{\cdot}91 \text{ square inches,}$$

has become

$$5{\cdot}41 \text{ square inches.}$$

Consequently, if we suppose the total weight supported by the valve to be 245 lbs., that weight, when the valve is shut, will represent a pressure per square inch of

$$\frac{245}{4{\cdot}91} = 50 \text{ lbs.};$$

and when the valve is raised, that same weight will only represent a pressure of

$$\frac{245}{5{\cdot}41} = 45{\cdot}27 \text{ lbs.}$$

The above established calculation, then, is to be depended on only, when the balance-screw can be lowered so as precisely to equilibrate the interior pressure, as has been said above, without, however, allowing the valve to rise. But the thing is not possible when the engine produces a surplus of steam beyond what its cylinders can expend, because this steam must necessarily have an issue. In this case, then, the pressure is to be found only by recurring afterwards to the barometer-gauge, as we shall presently indicate.

ARTICLE II.

OF THE INSTRUMENTS SPECIALLY DESTINED TO MEASURE THE PRESSURE.

Sect. I. *Of the Barometer-gauge, or Syphon-manometer.*

The calculations just proposed can only be established by measuring and weighing divers parts of the engine, which requires time and care, and can be effected only when the machine has ceased working. The great utility then is obvious of an instrument which, at once and by the mere inspection, shall give the exact measure of the pressure of the steam. With the aid of such an instrument, no case, not even that of the raised valve, opposes the smallest difficulty, nor needs any calculation.

Several instruments have been imagined for this purpose. The syphon-manometer, which we shall notice first, is represented in fig. 18. This instrument is not portative, for which reason those we shall describe in the following sections, and which, moreover, are much less expensive, will of course be preferred to it for the use of locomotives. However, as the manometer is the most accurate for the engine at rest, and as it may also serve for the graduation and verification of the others, its construction shall be shown here.

The instrument is established on the same prin-

ciple as the common barometer. *Mbm* is a tube containing mercury, which ought not to rise above the two points M and *m*. FG is a water reservoir, the use of which is to keep the branch *Mb* constantly full of water, in proportion as the mercury descends in that branch. Its diameter is purposely much greater than that of the tube, in order that the upper level of the reservoir be not sensibly lowered by reason of the water which it supplies to the tube. That level ought not to rise above the cock E, the use of which is to get rid of the surplus of water that may have been produced by condensation on some former experiment. R is an opening closed by a cock, and through which mercury or water may, when wanted, be introduced into the instrument. Lastly, C is a tap on which a tube is screwed, the other end of which reaches the boiler of the engine. This tube is flexible, and usually made of tin; it forms the communication of the mercurial-gauge with the engine. At the point where it reaches the engine, it is screwed on a tap fixed to the boiler, and kept close by a cock.

To prepare the instrument for use, an additional quantity of mercury is poured into it by the aperture R, in order to be sure that the instrument contains mercury at least to the height M*m*. After this, the screw-bolt M is unscrewed, so that if there happen to be too much mercury it may run off. When this is done the screw-bolt is replaced, and an additional quantity of water is also poured through R

into the reservoir FG, and, should there be too much, it is also allowed to run off through the cock E. Then the instrument is put in communication with the boiler. The steam, arriving through the tube C in the upper part of the reservoir FG, presses on the water by virtue of its elastic force; it consequently presses the mercury down in the branch M*b*, and makes it rise in the branch *mb* which is open at the top, until the weight of the mercury, thus raised, is equal to the pressure of the steam issuing from the boiler. A metal float borne on the surface of the mercury, at the point *m*, rises in proportion as that surface rises in the tube; and an index suspended to a thread which passes over a communication-pulley *p*, falls between the two tubes as the mercury rises in the branch *bm*, and shows upon a graduated scale the variations that occur in the level of the mercury in the different experiments. Supposing the length of the instrument from M to *b* be 6½ feet, or 78 inches, the ascending column may, if necessary, contain 156 inches of mercury; and as a column of 156 inches of mercury with a basis of 1 square inch weighs about 80 lbs., such a column may serve to measure an effective pressure amounting to 80 lbs. per square inch.

To graduate the scale of the instrument, we may begin by marking first the point zero. For this, the mercury and the water being poured in, as said above, the two branches must be left to communi-

cate freely with the atmosphere, and the point where the index stops will be the point sought, for that is the position which the float naturally takes when the branch Mb bears no more than the atmospheric pressure.

The other extreme point of the scale must afterwards be marked. Let π be the pressure we want to equilibrate; supposing the equilibrium established, let x be the height at which, by virtue of that same pressure π, the mercury will stand above its natural level in the branch m. The mercury having risen in the branch m to the height x, it must have fallen by an equal quantity in the other branch; for the mercury added on the one side can only proceed from what has been taken off on the other. The mercury in the branch M will therefore at the same time be at the point x', and the whole part of that branch, from the point x' to the point M, will be filled by the water from the reservoir. If through the point x' we draw an horizontal plane, the mercury which is under that plane will equilibrate itself in the two branches; we have therefore nothing to do with it, and need only consider the conditions of equilibrium for those parts which are above the plane in the two branches. Now, we have on the one side the pressure π, plus the weight of a column of water in height $Mx'=x$; and on the other side, we have a column of mercury in height $2x$, plus the weight of the atmosphere. P being the weight of the column of mercury, P′ that of the column of

water, and ρ that of the atmosphere, we shall have, since there is an equilibrium,

$$\rho + P = P' + \pi, \text{ or } P = P' + (\pi - \rho).$$

$(\pi - \rho)$, which is the surplus of the real pressure of the steam over the atmospheric pressure, is called the *effective* pressure; and in all high-pressure steam engines it is this which is to be considered. The column of mercury, the weight of which we have expressed by P, having for its basis the basis of the tube which we shall express by b, and for its height the height $2x$, its volume will be $2bx$; δ representing the density of the mercury, $2\delta bx$ will be the mass of the same column; and g expressing the accelerating force of gravitation, $2g\delta bx$ will be its weight: that is to say, we shall have

$$P = 2g\delta bx.$$

By the same reason, δ' being the density of the water, the weight P′ of the column of water will be expressed by $g\delta' bx$, its basis being also b, and its height $Mx' = x$. But the density of the water being expressed by 1, that of the mercury is expressed by 13·568; thus we have

$$\delta' = \frac{\delta}{13 \cdot 568},$$

and consequently

$$P' = \frac{g\delta bx}{13 \cdot 568}.$$

On the other side, the effective pressure $(\pi - \rho)$, in whatever manner it be expressed, may be replaced

by the weight of a column of mercury, that would produce the same pressure on the basis b. If then h be the height of that column, which it is easy to calculate, we shall have

$$\pi - \rho = g\delta bh;$$

and the equation of equilibrium will thus be

$$2g\delta bx = \frac{g\delta bx}{13{\cdot}568} + g\delta bh,$$

which gives

$$x = h \times \frac{13{\cdot}568}{26{\cdot}136} = h \times 0{\cdot}51913.$$

The height h of a column of mercury, which may represent a given pressure, is easily found; for we know that a column of mercury, one inch high, presses on its basis at the rate of 0·4948 ℔. per square inch. The height of any other column may thus be proportionably calculated. Wishing, for instance, to represent a pressure of 70 ℔s., we have

$$h = \frac{70}{0{\cdot}4948} \times \overset{\text{in.}}{1} = 141{\cdot}47 \text{ inches};$$

so that, by this value of h, the quantity sought x will be

$$x = 141{\cdot}47 \text{ in.} \times 0{\cdot}51913 = 73{\cdot}44 \text{ in.};$$

that is to say, that to correspond to an effective pressure of 70 ℔s., the height of the mercury must be 6 feet $1\frac{1}{2}$ inches.

The same calculation is applicable to any intermediate point that may be sought, but it would be

unnecessary trouble; for, knowing the point corresponding to zero, and that which corresponds to the *maximum* pressure of the instrument, we have only to divide the interval into equal parts, and the scale will be suitably graduated, having seen that the general value of x depends solely on the corresponding value of h, and is proportional to it.

When the pressure to be measured is but slight, as the apparatus need not then be of very great height, a manometer on the above principle may be fixed on the engine. Thus in the experiments on the pressure caused by the blast-pipe, which we shall report hereafter, we made use of a small manometer of this kind constructed by Mr. E. Woods, engineer to the Manchester and Liverpool Railway Company, and found it act commodiously and surely. It was capable of marking pressures amounting to 8 ℔s. per square inch. But to prevent the mercury from being driven out all at once in the sudden changes of pressure, or from making too great oscillations during the motion, recourse had been had to the known means of lessening the tube at the junction of the two branches of the syphon. This disposition had no other inconvenience than that of slightly diminishing the sensitiveness of the instrument.

The barometer-gauge which has just been described is not portative, in the case, at least, when it is required to measure high pressures. It must remain fixed to the wall where it has been once set up, and cannot accompany the engines in their

journey. If, the valve being once regulated, the engines preserved a constant pressure throughout their motion, this objection would be unimportant, and the instrument alone would satisfy all the wants. The valve being fixed at the intended working point, the corresponding pressure would be determined once for all, and provided no change were made at the spring of the valve, the pressure of the engine would be known at every moment of its work.

But this is not the case. Nothing is more variable than the pressure of the steam during the motion of the engines. When, for instance, the valve has been regulated for 50 lbs. per square inch, that is, so as to begin to give issue to the steam as soon as the pressure shall arrive at that point, we are not thence to conclude that the effective pressure will never, during the motion of the engine, be less than 50 lbs., nor that it will never be greater. Both these states will occur without any change being made at the valve. If the steam does not cause the valve to blow, the only derivable conclusion is that the effective pressure is under 50 lbs.; but in trying it then, either by loosening the spring or by the gauge, it will be found varying every moment according to the activity of the fire, the play of the pump, the inclination of the road, and many other circumstances apparently indifferent: at times the pressure will be only 15 or 18 lbs., then it will rise to 40 or 50 lbs. On the contrary,

if the steam is seen to blow at the valve, all that can be affirmed is that the effective pressure is above 50 lbs. But we must beware of believing, as at first we might be tempted to do, that because the valve rises as soon as the pressure reaches 50 lbs., it from that moment gives free vent to the steam, and that therefore the pressure of the latter can in no case rise above that point. Let the engine in this state be submitted to the gauge, and it will be seen that the pressure, instead of being restricted to 50 lbs., may be 60 lbs., and even more.

It will in effect be readily conceived that if a great part of the steam of the boiler escapes by the safety-valve, that steam can issue forth as fast as it is generated, only by raising the valve very high, in order to make for itself a sufficient passage. But the valve, as it rises, presses more and more on the spring. The latter then opposes a resistance by so much the greater; and consequently, the steam requires an elastic force by so much the greater, as it needs to create for itself a larger issue. As, moreover, the spring marks 50 lbs. only when the valve *begins* to rise, it is plain that the more its rising is increased, the more the corresponding pressure of the steam will exceed 50 lbs. per square inch.

The changes of pressure which we have just mentioned take place during the motion of the engines, that is to say, while they are separated from

the stationary gauge. The latter then can no longer be used directly to give the pressure of the steam; but, combining it with the observation of the safety-valve, a knowledge of the pressure may still be attained. In order to effect this, the engine must first be set at work, varying the starting point of the valve as it may appear necessary in the experiment; but two things are to be carefully noted, viz., the point at which the valve was fixed as the starting point, and its subsequent rise above that point. The experiment being ended, the engine must be brought back to the stationary gauge; then, fixing the valve successively at the different starting points which have been taken, and producing, moreover, by urging the fire, the divers elevations above those points, which have been observed during the experiment, the degrees of pressure to which they correspond may be written off from the barometer-gauge. Thus will then be formed, for each engine, a register which will render it easy to pass from the indications of the valve, during the work, to the actual pressures of the steam in the engine.

This mode, which is very practicable, is that which we employed when we had only the valve and the barometer-gauge to measure the pressure of the steam in locomotives; but the portable instruments, which we are about to describe, render this proceeding unnecessary, and are, besides, far more convenient.

Sect. II. *Of the Air-gauge.*

The air-gauge is represented in fig. 17. This instrument, long known, but recently applied to the use of locomotives, consists of a tube sealed at the top, in which a portion of air compressed indicates by the more or less diminution of its volume, the pressure exerted on it by the steam. This tube, exhibited at *t t*, is terminated at the upper part by a ball full of air, the object of which is to expose to compression a greater volume of air, without however requiring too great a length of tube. The tube, at the lower end, is terminated by another ball *b*, but this is filled with mercury, which rises also to a certain height *x* in the tube.

Near the top of the lower ball is a capillary aperture *o*, through which the steam can exercise a pressure on the mercury. The smallness of the aperture prevents the mercury from being easily spilt on conveying the instrument from place to place; but it would be better so to contrive as to be able, on occasion, to close it by means of a cock. In order that the lower ball may be put in contact with the steam, and that the upper portion of the instrument may still remain exposed to view, the tube is fixed in a metallic case, divided into two compartments by a horizontal partition CC; and the tube in traversing this partition, to which, moreover, it is hermetically sealed, has its lower ball enclosed in the lower compartment of the case,

and its upper part, on the contrary, in the superior compartment, which is opened through its whole length by a longitudinal groove *aadd*. The case fixes, by means of a moveable nut, to a tap on the boiler, and, on the turning of a cock, the steam penetrates freely, by the aperture O, into the lower compartment of the case. It consequently presses on the surface of the mercury through the passage *o*, and the mercury rises in the tube till the elasticity of the compressed air, together with the weight of the mercury raised in the tube, equilibrate the pressure exerted by the steam. Divisions marked on the edge of the longitudinal groove will then indicate the corresponding pressures of the steam.

The action of this instrument is founded on Boyle's or Mariotte's principle already explained, according to which the volume occupied by the air, under the same temperature, varies in the inverse ratio of the pressure which it sustains. It will readily be seen, in consequence, how the divisions of this instrument are established.

The capacity of the upper ball of the tube must first be measured by taking the weight of the mercury which precisely fills it, and measuring to what length along the tube the same weight of mercury would extend; then the capacity of the ball may be replaced, in the calculation, by an equivalent length of the tube.

Afterwards, having introduced a certain quantity

of mercury into the lower ball and into the tube, note is to be taken of the point at which the mercury stops when the instrument is exposed merely to the air. This point is evidently that which corresponds to a pressure equal to the atmospheric pressure, that is, to a total pressure of 14·71 English pounds per square inch, or, in other words, to the weight of a column of mercury 30 English inches in height.

This premised, in order to know the point corresponding to any other pressure of the steam, let P be that pressure in inches of mercury, and π the atmospheric pressure similarly expressed; let L also be the total length of the tube from the orifice *o* to the top, including in this measure the length of tube which represents the capacity of the ball filled with air, as has been explained above. Finally, let *h* be the height of the level of the mercury in the tube above the orifice *o*, when the instrument supports no more than the atmospheric pressure, and H the height of the same level, when the instrument is submitted to the pressure P.

It has been said that the spaces occupied by the compressed air are in the inverse ratio of the pressures which they sustain. Now, when the instrument is exposed to the atmospheric pressure π, since that pressure is then held in equilibrio by the resistance of the air contained in the tube, plus the weight of the column of mercury whose height is *h*, it is plain that the resistance of the

air, or the pressure which it sustains, is represented by

$$\pi - h.$$

Similarly, the resistance of the compressed air, under the external pressure P, is expressed by

$$P - H.$$

Finally, the spaces respectively occupied by the compressed air, under the external pressures π and P, are $L - h$ and $L - H$. We have therefore the analogy

$$\frac{L - h}{L - H} = \frac{P - H}{\pi - h};$$

whence is derived

$$P = H + (\pi - h)\frac{L - h}{L - H}.$$

Consequently, it will be easy, by means of this equation, to know the pressure which corresponds to a given division of the instrument; and after having thus determined a sufficient series of pressures, and inscribed them on a preparatory scale, then by interpolation may readily be deduced therefrom, a definitive and regular scale, indicating the elevations of the mercury for all the pressures required.

The problem may equally be resolved in a direct way, without any interpolation; that is to say, the elevation of the mercury corresponding to a determined pressure, may be found immediately; for the same equation, resolved above with reference to the

pressure P, may also be resolved with reference to H. It then gives

$$H = \frac{L+P}{2} - \frac{1}{2}\sqrt{(L-P)^2 + 4(\pi - h)(L-h)},$$

which expresses the elevation sought. It is however to be observed, that this equation is susceptible of another solution, in which the radical would be affected with the sign *plus* instead of *minus*. But the second solution, though it would satisfy the definitive equation of the calculation, does not apply to the question proposed; for, in the case of $P = \pi$, the equation must give $H = h$, and consequently the radical must be affected with the sign *minus*, as it is easy to verify.

The value of H thus found makes known immediately the point of the scale which corresponds to a determined pressure P, but as that value requires a calculation somewhat complicate, the former method will no doubt be preferred in practice. In either solution, the pressure of the steam is always expressed by the height of an equivalent column of mercury. Thus in the first solution, the result once obtained will have to be converted into pounds per square inch; and in the second solution, it will be requisite previously to convert the given pressures, from their usual expression, into an equivalent one in inches of mercury. But these mutations present no difficulty, since it is known that a pressure of 14·71 ℔s. per square inch is equivalent to a column of mercury of 30 inches in height.

From what has been said then, the divisions of the instrument may be marked for every point of the scale of pressures. It is however to be observed, that Mariotte's law, on which the preceding calculation is founded, is exact only so long as the air retains the same temperature in the different states of compression. In order that the divisions thus marked should be strictly accurate, the upper part of the instrument, that is, the portion filled with air, should always remain at the temperature of the external air. This result is obtained to a certain degree, even when the pressure, and consequently the temperature of the steam, become very considerable, because the upper part of the case lies open as much as possible to the contact of the air, and in the rapid motion of a locomotive, the contact of the external air incessantly renewed, tends to destroy all increase of temperature that might be transmitted from the steam to the air compressed in the tube.

In ordinary cases, then, the above-mentioned consideration may be dispensed with. It is clear however that this cause of error may easily be avoided, by adopting another proceeding to effect the graduation of the instrument. There may be attached first to the tube a provisional scale, divided merely into very small portions, and the instrument thus prepared may be put on a boiler in communication with a fixed barometer-gauge. Then as the barometer-gauge shall be seen to denote pressures

more and more elevated, the corresponding divisions of the provisional scale of the air-gauge may be observed, and consequently there will thus be formed a register from which the definitive scale of the instrument must afterwards be made out.

Albeit, if this mode have not been used to effect the primitive graduation of the instrument, it is that at least which ought to be used to verify that graduation, if the certainty of its accuracy be desired; and it is what we have always done before employing the air-gauge in our experiments. Moreover, it is plain that when the instrument is exposed to the external air, the mercury ought, save the slight modifications that may have occurred in the barometrical pressure of the atmosphere, to rise in the tube to the point marked for the atmospheric pressure, that is to say, to the *effective* pressure zero. This is then another verification not to be neglected, when recourse is not to be had to the preceding.

The air-gauge is portative and very commodious. It is usually not more than 10 inches long by an inch in thickness, and may be affixed with ease to all engines. But the divisions of the scale must be marked with the greatest accuracy, which presents some difficulty. The air too contained in the tube must be thoroughly free from all humidity, for that would become steam at the moment of the experiment. In fine, a drop of mercury lost in carrying the instrument, or a small quantity of water insinuated by means of the steam, into the lower ball,

may falsify the divisions. It is only then on being assured that the instrument is put out of hand by a careful workman, and as far as it may be possible, on having proved it by the barometer-gauge, that entire confidence is to be had in its indications.

SECT. III. *Of the Thermometer-gauge.*

The thermometer-gauge is an instrument as simple and as portative as the preceding; it is contained in a case similar to that of the air-gauge, and is similarly attached to the boiler by means of a moveable nut. This instrument, represented figure 19, is merely a thermometer, the ball of which is immersed in the boiler, and whose upper part rises above to expose to view the height to which the mercury rises.

To establish this instrument, it evidently suffices to take an ordinary thermometer and to replace the degrees of temperature by the corresponding degrees of pressure, in steam in contact with the liquid, according to the Table which we have given in the preceding chapter of this work. In order however that the degrees thus marked should be quite exact, it would be necessary to protect the ball of the thermometer against the compression which the elastic force of the steam tends to exercise on it, by a double casing, and that double casing would destroy all the sensitiveness of the instrument. In high pressures, the degrees of pressure indicated by the scale will be found then liable to a certain inaccu-

racy, unless, besides replacing the temperatures by their corresponding pressures, as has just been indicated, the latter be also corrected by taking account of the compression of the ball of the tube. In order to effect this, it will suffice to set up the instrument on an engine put in communication with a stationary barometer-gauge, and to observe, by the comparison of the two instruments, what correction ought to be made in the principal points of the scale. In this way will be avoided the causes of error that have been pointed out, and consequently the instrument can be verified when any doubt is entertained of its accuracy. We have invariably availed ourselves of it before using the instrument in our experiments.

The thermometer-gauge is both portative and commodious, but it wants accuracy when the pressure of the steam suffers rapid changes, which is constantly happening with locomotive engines: the time requisite for the instrument either to warm or to cool to the temperature of the steam, will not then allow it to indicate the pressure correctly. Another inconvenience still more serious is that, for high pressures, which are precisely those most generally wanted, the divisions are exceedingly small because the corresponding variations of temperature are very trifling. The instrument then becomes unsure, and, in the rapid motion of the engine, almost illegible, unless its dimensions, which are usually about 10 inches in length, were enlarged, and the instrument made less commodious on that account.

Sect. IV. *Of the Spring-gauge or Indicator.*

The above-mentioned defects of each of the preceding steam-gauges induce us to recommend trying, for locomotives, the use of the *indicator* of Mr. Watt, the construction of which properly falls into the department of engine manufacturers, whereas the other gauges require the aid of the optician.

This instrument is represented figure 23. It consists of a small brass cylinder, similar to the case of the two preceding gauges, and, like them, fixed temporarily to the boiler. Its lower part contains a piston P, susceptible of rising and falling in the cylinder, and admitting the steam to act under it. The area of the piston ought to be precisely one square inch. On its upper part is a rod *t*, which is maintained by a ring *c c*, in the exact direction of the axis of the cylinder. This rod acts against a spiral spring SS, similar to those of the ordinary spring-balances, and presses it with more or less force according as the piston is more or less raised by the action of the steam. A longitudinal groove *aabb* is made on the upper part of the instrument, so that an index *i*, moving with the head of the spring, juts out from the groove, and by means of a scale engraved on the edge, indicates the pressure sustained by the spring, and consequently the effective pressure of the steam under the piston, that is, in the boiler.

In order to divide the instrument, it suffices to

withdraw the piston and ascertain its precise weight. It must then be put back into its place, the cylinder reversed, and the piston loaded at first with a weight of 1 lb., diminished by the weight of the piston itself. The point at which, under this weight, the index rests is marked 1 lb.; then adding successively other weights of 1 lb., 2 lbs., &c., the respective points at which the index stops will be marked. This operation once finished, it is plain that when the steam shall have an elastic force of 1 lb., 2 lbs., &c. per square inch, it will make the index rise to the corresponding points of the scale; and the precaution of having included the weight of the piston in that of the first pound applied on the spring, causes the weight of that piston to come naturally into account in all cases as it ought to do. Thus the instrument will give immediately the pressure per square inch in the boiler.

The verification visibly reduces itself to measuring the diameter of the cylinder and placing anew some weights on the piston, to ascertain that the divisions of the scale are exact, that the friction of the piston has not varied, and that the spring has preserved its proper elasticity. That the piston may have precisely a square inch of surface, its diameter ought to be 1·1283 inch, or 1 inch $\frac{1}{8}$ and a fortieth of an eighth. The omission of this latter fraction, that is, the use of a piston $1\frac{1}{8}$ inch in diameter, would only cause an error of $\frac{1}{200}$ of a pound minus, which

would make a quarter of a pound on an effective pressure of 50 ℔s. per square inch.

SECT. V. *Comparative Table of the divers modes of expressing the pressure.*

As the pressure of the steam is expressed in several ways, and as in this work we use but one, we here subjoin a Table of correspondence of the divers modes of expressing it.

Comparative Table of the different modes of expressing the pressure of the steam.

Total or absolute pressure of the steam				Excess of that force above the atmospheric pressure, or pressure called *effective* in high-pressure engines,
in atmospheres.	in ℔s. per inch square.	in ℔s. per inch circular.	in inches of mercury.	in ℔s. per square inch.
1	14·71	11·55	29·92	,,
1·5	22·06	17·33	44·88	7·35
2	29·41	23·10	59·84	14·71
2·5	36·77	28·88	74·80	22·06
3	44·12	34·65	89·76	29·41
3·5	51·47	40·43	104·72	36·77
4	58·82	46·20	119·68	44·12
4·5	66·18	51·98	134·64	51·47
5	73·53	57·75	149·60	58·82
5·5	80·88	63·53	164·56	66·18
6	88·24	69·30	179·52	73·53
6·5	95·59	75·08	194·48	80·88
7	102·94	80·85	209·44	88·24
7·5	110·30	86·53	224·40	95·59
8	117·65	92·40	239·36	102·94

CHAPTER IV.

OF THE RESISTANCE OF THE AIR.

SECT. I. *Of the intensity of that resistance on the unit of surface.*

THE resistance of the air against the waggons cannot be regarded as a force to be neglected in calculations relative to motion on railways; for it is well known that trains, left to themselves, have at times been dragged to considerable distances by the mere impulse of the wind, and that engines in full course have literally been brought to a stand-still by momentary gusts of wind contrary to their direction.

It is necessary then to take into account the effects of the resistance of the air against the trains. The exact evaluation however of that resistance offers some difficulty. Borda's experiments,[1] as well as those of Rouse and Edgeworth,[2] prove that the resistance of the air, within the limits which we have to consider, increases in the ratio of the square of the velocity; and so far they are decisive: but

[1] Mémoires de l'Académie des Sciences, année 1763.

[2] Philosophical Transactions, 1782.

as to the absolute value of the resistance of the air, it cannot satisfactorily be determined by these experiments, because on larger surfaces being put to trial, there resulted resistances greater per unit of surface, leaving thus a doubt as to the choice to be made between these different results.

Nevertheless, till very lately, the only mode of estimating the resistance of the air was by the determinations of Borda. A work, but little known as yet, that of M. Thibault,[3] has however appeared, and furnished much more precise data on the subject.

Borda's experiments had been made in a circular motion, and Dubuat[4] had already thought that the singular anomaly which they presented, to wit, that of resistances increasing in a greater ratio than the surfaces, must proceed from the nature of the circular motion itself. He had in fact observed, that a body set in motion in a fluid always draws a portion of the fluid after it, and that this portion of fluid, attached to the moving object, is incessantly disturbed and driven back by the molecules of fluid which, after having sustained the shock of the moving surface, escape around its edges and rush behind it. There will always then be produced a partial vacuum, or diminution of pressure,

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[3] Expériences sur la résistance de l'air, par M. Thibault, lieutenant de Vaisseau, Brest.

[4] Principes d'Hydraulique.

or, as Dubuat has termed it, a *non-pressure*, behind the moving body; and as the definitive resistance against that body, is nothing else but the difference of the pressures exerted by the air against the front and hind surfaces, it follows that the resistance of the air against a moving body will always be increased, whenever the diminution of pressure behind the body shall become more considerable. Now if we suppose a surface of a given magnitude, set in motion in a straight line, there will be caused behind it a non-pressure, and the resistance suffered by the moving body will be the difference between the pressure of the air in front and the diminished pressure which subsists behind. If, after this, the body be submitted to a circular motion, it is evident that in proportion to the greater curvature of the line described by the body, the air, after passing over its edges, will by so much the more disturb the portion of fluid which follows it, and thus the pressure behind will be diminished; whence will result a greater resistance against the moving body. Again, if the latter be brought nearer the centre of motion, this same effect will be augmented. Definitively then, the resistance against a given surface, in a circular motion, will become greater as the surface is nearer to the centre of rotation; and in order that two surfaces of different magnitudes have to contend with an equal degree of disadvantage,—in other words, that the resistance of the air, per unit of surface, be the same for each,—those two surfaces

must be placed at distances from the axis, proportional to the sides of the squares which represent them.

This in effect has been verified by the experiments of M. Thibault, which have demonstrated, that in a circular motion, the apparent augmentation of the resistance of the air against large surfaces, compared with smaller ones, arises merely from the fact of their not being removed to a distance from the axis, proportional to the length of their side; that, subjected to this condition, the large surfaces, as well as the small, experience resistances really proportional to their extent; and that when non-subjected to this condition, the greater surfaces, on the contrary, may have to overcome resistances, per unit of surface, double those opposed to the surfaces of smaller extent. It is then to be concluded from those experiments that the circular motion cannot, with any accuracy, be used in determining the resistance of the air in a direct motion, unless the surfaces employed be of very small extent compared to the length of the radius of rotation.

The experiments of the same author confirm, moreover, two results already obtained by Dubuat with respect to liquids, and indicated by him with respect to fluids. The first of these results is, that the resistance against a body moving in an indefinite fluid, at rest, is less than the resistance experienced by the same body placed at rest in an

indefinite fluid moving against it, which seems to denote that a fluid in motion separates itself less easily than a fluid at rest. The second is, that a thin plate meets with a greater resistance from the air than a prismatic body presenting in front the same surface, and that the resistance diminishes according as the prism is longer. This circumstance is occasioned thus: the air having glided over the edges of a thin body, rushes immediately behind it with great rapidity, and carrying in its motion the portion of fluid, which we have mentioned above, produces a relative vacuum behind the opposed surface. But if the moving body be a lengthened prism, the air in passing along its sides loses a certain portion of its acquired velocity, and consequently, on reaching the hind face of the prism, extends itself behind it with a force more and more moderated; whence results that it produces there a partial vacuum, or non-pressure, less considerable than in the case of a simple surface. And as we have seen that the definitive resistance against a moving body is the difference between the pressure of the air in front and the partial vacuum created behind, it follows that longer bodies definitively suffer from the air a less resistance than bodies of inconsiderable thickness.

Besides, the experiments of M. Thibault have confirmed those of Borda, on the proportionality of the resistance of the air to the square of the velocity, within the limits of velocity that we have

to consider in this work. They have, moreover, demonstrated that if two square surfaces be placed so that one shall precisely screen the other, and at a distance apart equal to one of their sides, the resistance against the screened surface will be 7-tenths of the resistance suffered by the surface in front. It consequently results that, when two surfaces are separated by a considerable space relatively to their extent, the resistance of the air against the second is to be estimated nearly as if it were isolated in the air; but if, on the contrary, the two surfaces are very near each other, relatively to their extent, there is room to think that the screened surface may be almost entirely protected against the effect of the air, since a space equal to one side of the surface would be requisite for the air to exert against it a resistance equal to two-thirds of the resistance against an isolated surface.

Finally, uniting the results obtained by Borda, Dubuat, and M. Thibault, and limiting ourselves to the case of a body moving in the air at rest, which is the only case that occurs in this work, we have, to determine the resistance of the air, the following formulæ, in which Σ represents the front surface of a body traversing the air in a direction perpendicular to that surface, V the velocity of the motion, ϵ a co-efficient variable with the length of the body, and, lastly, Q the definitive resistance produced by the air against the body.

$Q = \cdot 0011896\ \epsilon\ \Sigma\ V^2$ . . Resistance of the air expressed in English lbs., the surface Σ being expressed in square feet, and the velocity V in English feet per second.

And in applying these formulæ it will be necessary, according to the case, to give to the letter ϵ the following values:

for a thin surface	$\epsilon = 1 \cdot 43$
for a cube	$\epsilon = 1 \cdot 17$
for a prism of a length equal to three times the side of its front surface	$\epsilon = 1 \cdot 10$

Sect. II. *Of the resistance of the air against the waggons, isolated or united in trains.*

From what we have just seen, it will be easy to estimate the resistance of the air against a prismatic body in motion, when its front surface and dimension in length are known. But as a waggon does not present a regular prismatic form, it becomes necessary first to consider how we may find what surface it really offers to the shock of the air.

The front surface of a waggon may be directly measured; it consists of two distinct parts, the surface of the load and that of the waggon itself.

The former of these surfaces necessarily varies according to the nature of the goods which form the load; and as to the surface of the waggon, properly so called, on railroads of 4 feet 8½ inches width of way, and for waggons with a single platform, it usually amounts to 14·33 square feet. But this is evidently not the only surface against which the air exerts its resistance; for the spokes of the wheels cannot turn rapidly as they do, during the motion, without meeting with a certain resistance from the air; and again the axle-trees, axle-boxes, springs, and hind-wheels of the waggon, are separated far enough from the similar pieces which precede them, not to be considered as wholly protected against the shock of the air.

Considering separately a wheel of 3 feet in diameter, like that of the ordinary waggons, and reducing the surface of all its spokes, whose divers points have different velocities according to their distance from the centre, to the surface which, being moved at the velocity of the circumference of the wheel, would suffer from the air an equivalent resistance, each wheel is found to offer in this respect a surface of 1·25 square feet. Adding then the direct surface offered by the rim of the wheel seen in front, as well as by the naves, axles, and springs, we arrive at this result, that each pair of wheels presents to the shock of the air a total surface of 7·03 square feet. Now, if we consider, either in an isolated waggon or in a train composed of several waggons, every pair of wheels

except the first, we shall observe that all present that extent of surface to the shock of the air; but as the whole of that surface is screened, to wit, the spokes by those which precede them in the motion, and the wheels, naves, and axles, by the similar pieces in the pair of wheels preceding them, we shall approximatively take this circumstance into account by assimilating the effects of the air on these successive pieces, to those observed by M. Thibault in the case of surfaces screened by each other and separated by an interval equal to the side of their square, which is not far from the truth in the case under consideration. We shall then reduce the above surface to two-thirds, and shall thus have 4·69 square feet, for the direct surface opposed to the shock of the air during the motion of the waggons, by each pair of wheels exclusive of the first.

Now, as to the fore-wheels of the first waggon, the surface of projection of the rims, springs, &c., is already reckoned in the total front surface of the waggon, but account must also be taken of the rotation of the spokes, which for this pair of wheels reduces the number 4·69 to 1·67 square feet. It follows then firstly that, for an isolated waggon, the addition to be made to its front surface, or rather to its surface of projection directly measured, for the fore and hind-wheels, should be 6 square feet. Furthermore, for the same case, as a loaded waggon presents, at a medium, a length equal to once and a

half the square root of its front surface, we should in the preceding formulæ make $\epsilon = 1 \cdot 15$.

As to the trains of several waggons, we at first see that, for the resistance of the wheels, an addition must be made to the transverse section of the train, of 9 square feet per intermediary waggon and of 6 square feet only for the first; but as the waggons composing the same train, though very near each other, are not however in contact, it is necessary further to seek upon what extent of surface, these waggons thus united still suffer the resistance of the air during their motion.

In order to effect this, we operated in the following manner:

On the 3rd of August, 1836, accompanied by Mr. E. Woods, engineer of the Liverpool and Manchester Railway, we took five waggons, of different heights, loaded with goods, and measured their front surfaces. These waggons were then drawn to the inclined plane of Whiston, an exact section of which will be given in the following chapter. They were then abandoned, separately, to their own gravity, and as the inclination of the plane was sufficient to decide their motion, they ran down of themselves, and having passed the foot of the plane, continued their motion along another plane much less inclined than the former, till they were brought to rest by the retarding forces, namely, the friction proper to the waggons themselves and the resistance of the air against their surface. After the waggons

had been submitted separately to this experiment, they were brought back on the inclined plane to the point from which they had first started, and again abandoned to gravity, but all united in one train.

As the friction proper to the waggons had evidently not varied, it is clear that if the latter experiment gave a total resistance greater than the sum of the frictions of the five separate waggons, augmented by the resistance of the air against the transverse section of the train, the surplus must be attributed to the indirect shock of the air against the successive surfaces of the intermediary waggons of the train; and, consequently, a valuation of that effect was to be obtained.

We shall explain, in the following chapter, in what manner the friction of the waggons was concluded from the circumstances of their motion on the two inclined planes; in this place it will suffice to relate the results of six experiments, made with a special view to determine the resistance of the air against the intermediary waggons. In the following Table, which contains these results, we give, for the first five experiments, the weight of each waggon and the surface it opposes to the shock of the air, including the wheels and accessory pieces, as has been indicated above.[5] In experi-

[5] When these experiments were published for the first time, an error had slipped into the measure of the front surface of the frame-work of the waggons; which error is corrected here.

ment VI., made on the waggons united, the surface carried into the eighth column is successively: first, that of the highest waggon of the train, augmented by the surface representing the resistance of the wheels and the screened parts; and, afterwards, the surface which gives, for the five waggons together, a friction equal to the sum of the frictions of the five waggons separate. The other columns make known the circumstances of the experiment, and consequently determine the friction of the waggons, as will be seen in the following chapter. To calculate the resistance of the air, we have taken in the case of the separate waggons $\epsilon = 1 \cdot 15$, as has been said above; and for the case of the connected waggons, as they formed a prism of a length equal to seven times its width, we have taken, according to the observations of Dubuat, $\epsilon = 1 \cdot 07$.

During these experiments the weather was fine, a slight air was perceptible in the contrary direction of the motion, but its action was so weak that a wind-gauge, exposed in an open place, could give no appreciable valuation of it.

As to the mode of experiment here employed, we must say, that when the resistance of the air against the front surface of the trains only is considered, it may appear that during the descent of the five waggons united, they must have pressed strongly one against the other, because the shock of the air, which was the resistance, exerted its effort against the front, whereas the gravity, which was the mo-

tive force, acted nearly in the centre of the mass in motion. Hence, therefore, it might be concluded, that this pressure of the waggons one against the other would throw them out of square upon the line, and consequently, in this case, make their friction appear greater than it really was. But it must be observed, that in experiment VI. the waggon of greatest section was put last in the train, and again, that the resistance of the air exerted itself against each intermediate waggon, which divided that resistance over the different points of the train, instead of concentrating it on the front surface. Moreover, a pressure of the waggons one against the other may, in effect, throw them out of square when they are connected by stiff bars, because the shortening of the train then tends to set those bars across, and thus drive the waggons against the rails on either side. But the waggons here employed were not of this kind; they were joined together merely by chains, and in that state the mutual contact took place by the projecting ends of the frame on each side; consequently, it could only tend to maintain them more directly on the road, since, in such a system of junction, the shortest line the train can form, or that which is determined by the pressure of the hinder waggons, is not a crooked line as in the case of the stiff bars, but a straight and direct line from one end of the train to the other. None of these accessory effects then occurred in the experiments which we are about to report.

Experiments on the resistance of the air against the trains.

Number of the experiment.	Date of the experiment.	Designation of the train.	Weight of the train.	Height of fall on the first plane.	Distance traversed on the first plane.	Height of fall on the second plane.	Distance traversed on the second plane.	Effective surface exposed to the shock of the air.	Friction of the waggons per ton.	Total friction of the train.
			tons.	feet.	feet.	feet.	feet.	sq. feet.	lbs.	lbs.
I.	Aug. 3, 1836.	1 waggon	4·36	34·61	3300	2·20	3003	57	5·99	26·13
II.	id.	1 waggon	5·66	34·61	3300	2·48	3768	50	6·15	34·80
III.	id.	1 waggon	4·38	34·61	3300	2·16	2889	77	4·74	20·77
IV.	id.	1 waggon	4·43	34·61	3300	2·19	2970	54	6·52	26·86
V.	id.	1 waggon	4·45	34·61	3300	1·63	2064	91	6·10	27·15
									5·92	137·71
VI.	id.	5 waggons	23·28	34·61	3300	3·10	5376	127	5·97	138·86
								130	5·90	137·22

From this Table it appears, that limiting ourselves in experiment VI., to taking account of the resistance produced by the rotation of the wheels and by the screened pieces of the frame-work of the waggons, the friction of the five waggons deduced from this experiment, seems to be more considerable than the sum of the frictions of the same five waggons, deduced from the preceding experiments; and that it is only by adding 3 square feet more to the surface exposed to the shock of the air in experiment VI., that we are enabled to put the result of that experiment in harmony with those of the separate waggons. We must then conclude, that besides the resistance opposed by the air against the wheels and the screened pieces of the frame-work, there was still a surface of 3 square feet for the four waggons which followed the first, or a surface of 1 square foot per waggon, exposed to the shock of the air during the motion. That is to say, the air after the passage of the first waggon, rushed between that waggon and the following one, and notwithstanding the small interval which separated them, it still exerted on the second waggon a certain action, the intensity of which might be represented by the shock of the air against 1 square foot of direct surface.

Consequently, adding this new surface to that already obtained to represent the motion of the wheels and accessory pieces, we see that when a train of waggons is in motion on a railway, it is

necessary, in order to estimate the effects of the resistance of the air against its progression, to take as resisting surface that of the waggon of greatest section, augmented by 10 square feet per intermediary waggon, and by 6 square feet for the first waggon, including of course in this number the engine itself and its tender.

On railways of about 5 feet width of way, the surface of the highest waggon may at a medium be reckoned at 70 to 74 square feet; we may then esteem, in general, the resisting surface of a train of waggons at 70 square feet, plus as many times 10 feet as there are carriages in the train, including the engine and its tender. If the train consists of diligences, as their surface is from 60 to 64 square feet, then in the preceding estimation the number 70 must be replaced by the number 60.

If the road has a wider way, or if the carriages offer a surface different from that we have just indicated, the carriage of greatest section must be measured, and that measure used, instead of the number 70 or the number 60 of the above calculation. If the wheels of the waggon are more than 3 feet in diameter, there will likewise be an addition to make, to take account of the greater surface which they expose to the shock of the air during the motion. This addition would be about 3 square feet per waggon, for wheels of 5 feet in diameter instead of 3. Finally, if the interval between the

waggons, instead of being about 2 feet, as it was in experiment VI., and as it is at a medium on ordinary railways, considering the different kinds of carriages and the inequalities of their loading, were augmented by any important quantity, there might also be some addition to make for the effect of the air against the loads of the successive waggons; but as our determination in this respect gave something less than 1 square foot per waggon, and as the interval between the waggons could not be augmented by any thing considerable without being liable to inconveniences in practice, we deem that 1 square foot per waggon may comprehend nearly all cases.

When the effective surface presented to the shock of the air shall be known by the preceding calculation, it must be substituted for the letter Σ in the formulæ given above, putting at the same time for ϵ, its value suitably to the length of the prism formed by the train of waggons. According to the variation of ϵ observed by Dubuat for prisms of divers proportions, it will be found that in the case of a train of 5 waggons, we must make $\epsilon = 1 \cdot 07$, and that the case of a train of 25 waggons would require $\epsilon = 1 \cdot 04$. In order then not to have to return continually upon these considerations we will take as a medium $\epsilon = 1 \cdot 05$, which is suitable to a train of 15 waggons, and expressing at the same time, in the formula given above, the velocity in miles

per hour, we shall have, in fine, to express the resistance of the air against a train of waggons in motion, the following formula:

$Q = \cdot 002687\ \Sigma\ v^2$ . . . Resistance of the air, in pounds, the effective surface of the train or the quantity Σ being expressed in square feet, and the velocity of the motion in miles per hour.

SECT. III. *Table of the resistance of the air against the trains.*

To dispense with all calculation relative to the resistance of the air, we here subjoin a Table showing its intensity, for all velocities from 5 to 50 miles per hour, and for surfaces of from 10 to 100 square feet. Were it required to perform the calculation for a velocity not contained in the Table, it would evidently suffice to seek the resistance corresponding to half that velocity and to multiply the resistance found by 4; or, on the contrary, to seek the resistance corresponding to the double of the given velocity, and to take a quarter of the result. So, the resistance of the air against a surface of 100 square feet, at the velocity of 50 miles per hour, is equal to four times the resistance of the air against the same surface, at the velocity of 25 miles per

hour. As to surfaces greater than 100 square feet, they must be decomposed into surfaces less than 100 feet, and then the Table will still give the results required; for the resistance against a surface of 120 square feet is evidently nothing more than the sum of the resistances against one surface of 100 square feet and one of 20 square feet.

By means of the Table in question will be obtained, without calculation, the resistance of the air expressed in pounds, for any velocity of the moving body; but it is to be observed, that the Table supposes the atmosphere at perfect rest. If then there be a wind of some intensity, favourable to the motion or contrary to it, account must be taken thereof. In order to effect this, it will suffice to observe that if the wind is favourable, the body will move through the air only with a velocity equal to the difference between its own absolute velocity and that of the wind; and that if, on the contrary, the wind is opposed to the motion, the effective velocity of the body through the air will be equal to the sum of its own velocity augmented by that of the wind. In this case, then, the velocity of the wind must first be measured, by abandoning a light body to its action, and noting the time in which it traverses a space previously measured on the ground; or else an anemometer may be used for the purpose. Then the velocity of the wind must be subtracted from that of the train in motion or added to it, according to the case; and that difference or that sum is the velocity to be

sought in the Table, or substituted in the formula, to obtain the corresponding resistance against the whole train.

If the wind, instead of being precisely contrary or favourable to the motion, should exert its action in an oblique direction, it would tend to displace all the waggons laterally; and consequently, from the conical form of the wheels, all those on the farther side from the wind would turn on a larger diameter than those on the side towards the wind. The resistance produced will therefore be the same as that which would take place on a curve on which the effect of the centrifugal force were not corrected, and that resistance would necessarily be very considerable; but as we have made no experiment on this subject, we shall not dwell on it any longer here.

Practical Table of the resistance of the air against the trains.

Velocity of motion, in miles per hour.	Resistance of the air, in lbs. per square foot of surface.	Resistance of the air, in pounds; the effective surface of the train, in square feet, being:								
		20	30	40	50	60	70	80	90	100
miles.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.
5	·07	1	2	3	3	4	5	5	6	7
6	·10	2	3	4	5	6	7	8	9	10
7	·13	3	4	5	7	8	9	11	12	13
8	·17	3	5	7	9	10	12	14	15	17
9	·22	4	7	9	11	13	15	17	20	22
10	·27	5	8	11	13	16	19	22	24	27
11	·33	7	10	13	16	20	23	26	29	33
12	·39	8	12	15	19	23	27	31	35	39
13	·45	9	14	18	23	27	32	36	41	45
14	·53	11	16	21	26	32	37	42	47	53
15	·60	12	18	24	30	36	42	48	54	60
16	·69	14	21	28	34	41	48	55	62	69
17	·78	16	23	31	39	47	54	62	70	78
18	·87	17	26	35	44	52	61	70	78	87
19	·97	19	29	39	49	58	68	78	87	97
20	1·07	22	32	43	54	65	75	86	97	107
21	1·19	24	36	47	59	71.	83	95	107	119
22	1·30	26	39	52	65	78	91	104	117	130
23	1·42	28	43	57	71	85	100	114	128	142
24	1·55	31	47	62	78	93	109	124	140	155
25	1·68	34	50	67	84	101	118	134	151	168
26	1·82	36	55	73	91	109	127	146	164	182
27	1·96	39	59	78	98	118	137	157	176	196
28	2·11	42	63	84	106	127	148	169	190	211
29	2·26	45	68	90	113	136	158	181	203	226
30	2·42	48	73	97	121	145	169	194	218	242
31	2·58	52	77	103	129	155	181	206	232	258
32	2·75	55	83	110	138	165	193	220	248	275
33	2·93	59	88	117	147	176	205	234	264	293
34	3·11	62	93	124	156	187	218	249	280	311
35	3·29	66	99	132	165	197	230	263	296	329
36	3·48	70	104	139	174	209	244	278	313	348
37	3·68	74	110	147	184	221	258	294	331	368
38	3·88	78	116	155	194	233	272	310	349	388
39	4·09	82	123	164	205	245	287	327	368	409
40	4·30	86	129	172	215	258	301	344	387	430
41	4·52	90	136	181	226	271	316	362	407	452
42	4·74	95	142	190	237	284	332	379	427	474
43	4·97	99	149	199	249	298	348	398	447	497
44	5·20	104	156	208	260	312	364	416	468	520
45	5·44	109	163	218	272	326	381	435	489	544
46	5·69	114	171	228	285	341	398	455	512	569
47	5·94	119	178	238	297	356	416	475	535	594
48	6·19	124	186	248	310	371	433	495	557	619
49	6·45	129	194	258	323	387	452	516	581	645
50	6·72	134	202	269	336	403	470	538	605	672

CHAPTER V.

OF THE FRICTION OF THE WAGGONS ON RAILWAYS.

SECT. I. *Necessity of new inquiries on this subject.*

FROM the description we have given of the engine, it has been seen that the steam, acting on the pistons, communicates to the wheels a rotatory motion, which must infallibly propel the engine, provided the train which follows it do not oppose a resistance greater than the force it commands.

An important inquiry then, as to the motion of locomotives, consists in determining the resistance caused by the trains which they have to draw.

These trains are formed of a number more or less considerable of carriages called waggons, which are loaded with goods. Their resistance to the motion depends not only on their weight, but on the state of the railway and on the more or less perfect construction of the carriages. The object in view in the making of a railway being to produce a road perfectly hard and smooth, on which the carriages shall roll easily, if the railway happen to be indifferently maintained or otherwise to deviate from the conditions for which it has been established, it is plain

that the resistance opposed by the train along the rails will be by so much the greater. The same will occur if the carriages, from defective construction or want of repair, have a considerable friction.

This observation shows that the force necessary to move a given weight, a ton for instance, may not be always the same, either on all railways, or with all kinds of carriages. On rails perfectly even, and with waggons well constructed and well greased, the draught of a ton may require a force of but 6 ℔s. We mean that a weight of 6 ℔s. suspended by a cord over a pulley, would suffice in this case to move, or at least to maintain in motion, a carriage weighing a ton. On another railway, on the contrary, and with carriages of a different construction, the same load of a ton may require a much greater force.

The old waggons on which some experiments had been made, were supposed to require a force of 10 or 12 ℔s. for each ton of weight of the load. They had afterwards been improved, but had not been submitted to any experiment made on a large scale and in the regular working state. On the first introduction of the new waggons, an essay was indeed made on a single one and at the moment it left the workmen's hands. But as this waggon had been carefully oiled expressly for the trial; as it had as yet received no shock to bend the axle-trees, or to throw the wheels out of square; as the wheels were new and perfectly round; as, in fine, the rails had

been carefully swept for the purpose, the result of such an experiment could hardly be considered as a practical result. So, on the Liverpool Railway, the friction of the trains was still valued at 10 lbs. per ton.

These uncertain data could not suit a new work, or calculations made on modern waggons; and therefore we undertook, in order to determine the friction of waggons, the series of experiments which we are about to relate.

Sect. II. *Of the friction of waggons determined by the dynamometer.*

The most natural means of attaining the determination of the friction or resistance of the waggons seemed to be to employ the dynamometer, since it gives immediately the force of traction necessary to effect the motion; but, as the action of drawing, whether by men, or any other animated mover, is performed by pulls, the dynamometer merely oscillates between limits wide apart, and can give no certain result. It appeared to us, however, that if the traction were performed by an engine whose strain is always equal, and whose motion too is regulated by the mass of the train itself, the dynamometer would, perhaps, have but slight oscillations, and that the pulsations of the engine would be insensible, especially on the hinder carriages.

For this reason, at the moment the engine LEEDS started with a train of twelve waggons, when the whole mass was set in motion, and that motion continued at the uniform velocity of about three or four miles per hour, the drawing chain of the last three waggons was detached and replaced by a circular spring-balance, previously disposed for the purpose. The rod of the balance was fixed to the hinder part of the ninth waggon, and the three following ones, which were the last of the train, were fastened to the spring. The experiment took place on the half mile from 1½ to 2 of the Liverpool and Manchester Railway, on a space which is exactly level.

We expected to see the balance nearly invariable; we were, however, deceived. The style maintained itself most frequently about the point marking 100 lbs., but it was continually subject to great variations, which went from 50 lbs., the least, to 170 lbs., the greatest; and even, in a sort of extraordinary pull, which the engine gave at times, the needle was seen to fly to the end of the balance, which indicated 220 lbs. The latter case, however, only occurred accidentally, and immediately after the needle returned to its habitual point of about 100 lbs., and resumed its oscillations between 50 lbs. and 170 lbs. After having waited in vain to see the motion regulate itself in a more steady manner, it appeared to us that the experiment was not susceptible of greater precision.

The variation of the needle between 50 lbs. and 170 lbs. gave the medium of 110 lbs., and the three waggons weighed together 14·27 tons; thus the experiment gave $\frac{110 \text{ lbs.}}{14 \cdot 27}$ or 7·70 lbs. of resistance per ton. But, as this mean was much too uncertain, it appeared necessary to recur to another mode of experiment.

In consequence, a convenient spot being chosen on the Liverpool and Manchester Railway, near the foot of the *Sutton* inclined plane, at the distance of 11½ miles from Liverpool, the level of it was taken with strict accuracy in tenths of an inch, and the experiments were begun on the principle we are about to explain.

Sect. III. *Of the friction of carriages, determined by the circumstances of their spontaneous descent and stop upon two consecutive inclined planes.*

Suppose a system of two wheels joined together by an axle-tree fixed invariably to each (fig. 31), and loaded with a given weight resting at N, on a chair on which the axle-tree may turn freely. Let this system be placed on an inclined plane, along which it is liable to roll. Again, at the foot of the first plane, let there be another inclined plane continuing the former, and on which the rolling body may continue its motion. Finally, suppose that the

former of the two planes be sufficiently inclined to cause the body placed upon it to roll down spontaneously, and by its own weight; and that the second, on the contrary, though descending in the same direction, be so slightly inclined that the body, were it simply placed upon it, would be kept still by the friction.

In these circumstances it is plain that the body, abandoned to itself, will first roll down the first inclined plane, accelerating its velocity gradually, and that on reaching the second plane, its motion, on the contrary, will slacken by degrees, till having exhausted its acquired velocity, it finally be brought to rest.

If the body experiences a considerable friction, it will assume little velocity in its descent on the first plane, and will promptly come to a stand on the second. If, on the contrary, the friction has but little intensity, the body will acquire a great velocity on the first plane, and will prolong its course considerably on the second. Comparing, then, the height which the body has descended, with the distance it has traversed before stopping, it will be possible to recognise what intensity of friction it has been submitted to in its course.

To obtain an analytical relation giving the solution of this problem, it will be proper first to form the equation of the motion of the body on the two planes, and therefrom to deduce the velocity

it will acquire in descending the first plane, and the distance it will traverse on the second, in virtue of that velocity.

Hence, the inquiry will comprise three successive questions: 1st. To determine the effective accelerating force to which the centre of gravity of the system will be subject in its motion; 2nd. To deduce from this the velocity acquired by the moving body at the foot of the first plane; and 3rd. To conclude finally the distance it will have traversed on the second plane at the moment when the friction shall have reduced its velocity to nothing.

The determination of the effective accelerating force required, will be effected by means of the principle that the motive forces applied and effective must be in equilibrio, that is to say, must have their resultants equal and opposed, as well as their momenta equal and opposite when the effective forces are taken in the contrary way to their direction.

Now, the motive forces applied to the system, are:

1st. The weight of the body of the waggon resting on the chair of the axle-tree, and which we will call P. This force, acting vertically, will decompose into two others: one, in the direction of the plane, will have an immediate effect, and will draw the body along the plane; the other, perpendicular to the direction of the plane, will produce a pressure of the chair upon the axle and of

the rim of the wheel upon the rail, and will consequently cause on each of these points a friction, of which we shall presently express the effect. If we call θ' the angle of the plane with the horizon, the first of these two forces will be P sin. θ', and the second P cos. θ', and the two together may replace the primitive force P.

2nd. The weight of the system of the two rolling wheels, with their axle. We will call this force p, and will also replace it by two others p sin. θ' and p cos. θ', the one parallel, the other normal to the plane.

3rd. The adhesion of the wheel on the rail at T. This force acts along the plane contrariwise to the motion of translation. It is this force which produces the rotation of the wheel, by preventing its circumference from sliding without turning during the motion along the plane. We will express this force by the weight T, which shall be equivalent to it.

4th. The resistance of the air against the surface of the system set in motion. Experience has demonstrated that this force is proportional to the square of the velocity, and we will, in consequence, express it by Qv^2, Q being the weight which represents its intensity against the known surface of the moving mass, in the case of $v=1$.

5th. The normal force P cos. θ', which has been mentioned above, produces a pressure of the chair against the axle, and thus its effect will be to cause

a friction at the point of contact. But as experience has proved that the friction of bodies sliding on each other is a force proportional to the pressure, and independent of the velocity or the extent of the surfaces in contact, we will express the friction in the present instance by f' P cos. $\theta,'$ f' being a constant quantity; and that force will act tangentially to the circumference of the axle, and in the direction contrary to the motion of rotation.

6th. Lastly, the same force P cos. $\theta,'$ and moreover the force p cos. θ' produced by the weight of the wheel, will exert a pressure at the point of contact T of the wheel on the rail. There will result from this pressure a friction at T; but as at this point the two surfaces in contact do not slide, but merely roll one upon the other, the friction produced will be of the second species. And, as it is known from Coulomb's experiments, that the intensity of this friction is inversely as the diameter of the wheel, we will express it by

$$f'' \, (\mathrm{P}+p) \cos. \, \theta' \times \frac{1}{\mathrm{R}};$$

f'' being a constant quantity, which is easily deduced from the direct experiments made on this subject, with wheels of 3 feet diameter, or of 1·5 feet radius. This force, in fine, will act tangentially to the circumference of the wheel, and contrarily to the motion.

Such are the divers motive forces applied to the system.

On the other hand, if we express by g the gravity; by ϕ the *effective* accelerating force which produces the motion of translation of the centre c of the wheel; by ψ the effective accelerating force which produces the rotation of a point of the wheel situated at the distance 1 from the axle, and, in fine, by $\frac{p}{g} k^2$ the momentum inertiæ of the wheel, it is plain that the mass of the body being $\frac{P+p}{g}$, the *effective* motive force which produces the motion of translation will be

$$\frac{P+p}{g} \phi,$$

and the momentum of the effective motive force of the motion of rotation, will be

$$\frac{p}{g} k^2 \psi.$$

Consequently, since the motive forces effective and applied ought to be in equilibrio, as well in virtue of their direct intensities, as in virtue of their momenta about the axis of rotation, we shall have, expressing by R and r the radii of the wheel and axle, the two following equations:

$$P \sin. \theta' + p \sin. \theta' - T - Q\, v^2 = \frac{P+p}{g} \phi,$$

$$T R - f' P r \cos. \theta' - f'' (P+p) \cos. \theta' = \frac{p}{g} k^2 \psi.$$

Furthermore, as the velocity of the circumference

of the wheel is equal to the velocity of translation of the centre, it follows that the velocity of rotation of a point situated at the distance 1 from the axis of the wheel will be to the velocity of translation in the ratio of 1 to R; and, consequently, the same relation will exist between the accelerating forces, or

$$\psi = \frac{\phi}{R}.$$

Substituting then this value in the second of the two equations above, and deducing the value of T, we obtain, firstly,

$$T = f' P \cos.\theta' . \frac{r}{R} + f'' (P+p) \cos.\theta' . \frac{1}{R} + \frac{p}{g} \cdot \frac{k^2}{R^2} \phi.$$

Supposing the planes but little inclined, we have very approximatively $\cos.\ \theta' = 1$. Besides, if we make

$$f' P \frac{r}{R} + f'' (P+p) \frac{1}{R} = f (P+p),$$

the expression of the quantity T will become

$$T = f (P+p) + \frac{p}{g} \cdot \frac{k^2}{R^2} \phi.$$

Consequently, substituting this in the first equation, we derive in fine for the value of ϕ,

$$\phi = \frac{g}{1 + \frac{p}{P+p} \cdot \frac{k^2}{R^2}} (\sin.\ \theta' - f - \frac{Q}{P+p} v^2).$$

As the weights P and p are known, as well as the force Q, which expresses the resistance of the air,

at the unit of velocity; as, besides, the momentum inertiæ $\frac{p}{g} k^2$ is determined *à priori*, and as all these quantities are constant, we may, in order to simplify, make

$$\frac{Q}{P+p} = q \text{ and } \frac{g}{1 + \frac{p}{P+p} \cdot \frac{k^2}{R^2}} = \frac{g}{1+n} = g'.$$

Then the accelerating force to which the motion of translation of the system is subjected, will be definitively

$$\phi = g' (\sin. \theta' - f - qv^2);$$

and the motion of translation of the moving body may be considered as produced in space, by virtue of that force alone.

The foregoing gives then the solution of the first portion of the problem, namely, the determination of the accelerating force. It now remains to deduce from the knowledge of the accelerating force, the velocity communicated to the mass by its descent on the first plane, and the distance to which it will be driven on the second plane by virtue of that velocity. In order to effect this, we will first consider the motion on the first plane.

Let x be the distance traversed on the plane, when the body has acquired the velocity v; the quantity ϕ being the accelerating force of the motion, and that accelerating force being equally expressed in general by the expression $\frac{v\,dv}{dx}$, we have

$$\frac{v\,dv}{dx} = g' \,(\sin.\, \theta' - f - qv^2);$$

or making for a moment, $\sin.\, \theta' - f = b'$,

$$\frac{v\,dv}{b' - qv^2} = g'\,dx.$$

This will be then the equation of the motion. Integrating it, and observing that the velocity is null at the point of starting, or that $x = o$ gives $v = o$, it will be replaced by the following,

$$2qg'x = \log.\, \frac{b'}{b' - qv^2};$$

or, expressing by $e = 2{\cdot}7182818$, the base of the Neperian logarithms, it will be

$$e^{2qg'x} = \frac{b'}{b' - qv^2},$$

which gives

$$qv^2 = b'\, \frac{e^{2qg'x} - 1}{e^{2qg'x}}.$$

This relation then makes known the velocity acquired by the body after it has traversed the distance x on the first plane.

It will be recognised therein that the greater x is, the greater also becomes v; and for $x = \infty$ we have $qv^2 = b'$ or $\phi = o$; that is to say, the motion, as it continues, approaches more and more to uniformity. But it will be remarked that, since the value of qv^2 may be written under the form

$$qv^2 = b' \left(1 - \frac{1}{e^{2qg'x}}\right),$$

the motion will be sensibly uniform as soon as x becomes large enough to make the fraction of the second member inconsiderable with reference to 1; and as x is here an exponent, it is plain that this condition will quickly be fulfilled. From this point, then, we shall have

$$qv^2 = b',$$

and the motion will no longer differ from uniformity but by an inconsiderable quantity. This in fact, as experience proves, does really take place within a very short time.

The preceding inquiry gives then the velocity at any point whatever of the first plane; and if we call l' the length of the plane, and V the velocity of the body the moment it arrives at the bottom of the plane, we see from the equation just obtained, that this velocity will be

$$q\mathrm{V}^2 = b'\,\frac{e^{2qg'l'} - 1}{e^{2qg'l'}};$$

which solves the second part of the problem.

Now that we have the velocity of the moving body at the foot of the first plane, and consequently at the beginning of the second, since they are supposed to be united by a continued curve, the question is to determine at what point of the second plane the body will stop, which will lead us to the definitive solution of the problem.

To this effect must be considered the motion of the body on the second plane. Calling θ'' the angle

it forms with the horizon, as all the circumstances of the motion remain the same as before, except only that the inclination of the plane is less, we shall have by analogy

$$\frac{v\,dv}{dx} = g' \,(\sin.\,\theta'' - f - qv^2).$$

And as we have supposed that on the second plane gravity is less than friction, that is to say, we have $\sin.\,\theta'' < f$, we will here make

$$\sin.\,\theta'' - f = -\,b''.$$

Then the accelerating, or rather retarding force, since it is negative, of this second motion, will be expressed by

$$\frac{v\,dv}{dx} = -\,g' \,(b'' + qv^2).$$

Integrating this equation then, and observing that at the beginning of the plane the velocity is V, or, in other words, that $x = o$ gives $v = \mathrm{V}$, it will be replaced by the following, which is suitable to every point of the motion,

$$2qg'x = \log.\,\frac{b'' + q\mathrm{V}^2}{b'' + qv^2}.$$

Consequently, if l'' stand for the distance traversed by the body on the second plane, at the moment when its velocity becomes null, this equation will still subsist if we make in it at once

$$x = l'', \quad v = o.$$

Thus it will become

$$2qg'l'' = \log. \frac{b'' + qV^2}{b''},$$

or

$$e^{2qg'l''} = 1 + \frac{qV^2}{b''};$$

and putting for qV^2 its value concluded from the motion on the first plane, this equation will become

$$\frac{b'}{b''} = \frac{e^{2qg'l''} - 1}{e^{2qg'l'} - 1} e^{2qg'l'}.$$

Finally, if instead of g', b' and b'', their values be restored, and if, moreover, h' stand for the vertical height which the body has descended on the first plane, and h'' the vertical height which it has descended on the second, which gives

$$\sin. \theta' = \frac{h'}{l'} \text{ and } \sin. \theta'' = \frac{h''}{l''},$$

the relation just obtained above will become

$$\frac{h' - fl'}{fl'' - h''} = \frac{l'}{l''} \cdot \frac{e^{\frac{2qgl''}{n+1}} - 1}{e^{\frac{2qgl'}{n+1}} - 1} e^{\frac{2qgl'}{n+1}}.$$

This is the definitive relation between the co-ordinates of the points of departure and arrival of the moving body, the various data of the problem and the friction sought.

When in this equation we suppose $q = o$, the second member reduces itself at first to $\frac{o}{o}$, but making

$$e^{\frac{2qg}{n+1}} = y,$$

it changes to

$$\frac{l'}{l''} \cdot \frac{y^{l''}-1}{y^{l'}-1} y^{l'};$$

and dividing by $y-1$, it becomes

$$\frac{l'}{l''} \cdot \frac{y^{l''-1}+y^{l''-2}+y^{l''-3} \ldots\ldots +1}{y^{l'-1}+y^{l'-2}+y^{l'-3} \ldots\ldots +1} y^{l'},$$

which for $q=o$ or $y=1$, reduces itself to $\frac{l'}{l''} \times \frac{l''}{l'} = 1.$

Wherefore in this case, that is to say if the motion took place in a vacuum, the above relation would become

$$\frac{h'-fl'}{fl''-h''}=1\ ; \text{ whence } f=\frac{h'+h''}{l'+l''}.$$

Consequently, we should then have the friction required, by dividing the sum of the vertical heights which the body has descended, by the sum of the spaces it has traversed; and it will be remarked that in this case, since there would be no resistance of the air, the motion of the body on the first plane could never attain uniformity.

We have seen what the general relation becomes, on supposing $q=o$; if moreover we make $f=o$, that relation reduces itself to

$$h'+h''=o \quad \text{or } h''=-h'.$$

Consequently were there neither friction nor resistance of the air, the moving body would rise on the second plane, supposing it inclined contrari-

wise to the first, to a height equal to that from which it has descended; and we quote these results because, being easily deduced from the direct examination of each supposition, they serve here to verify the calculation.

To return to the general formula, making in it

$$\mathrm{Y}=\frac{l'}{l''}\cdot\frac{e^{\frac{2qgl''}{n+1}}-1}{e^{\frac{2qgl'}{n+1}}-1}e^{\frac{2qgl'}{n+1}},$$

we perceive that it may be written under the form

$$\frac{h'-fl'}{fl''-h''}=\mathrm{Y};$$

whence is derived for the value of the friction f,

$$f=\frac{h'+h''\mathrm{Y}}{l'+l''\mathrm{Y}}.$$

Thus, when, after having submitted a body of a determined weight, to the above experiment, on two planes of known inclination, the quantities h' l' h'' and l'' shall have been found, it will suffice to calculate the corresponding value of Y, and introducing it with the other data in the expression of f, we may deduce the value of this latter quantity, which will be the friction sought.

This method has the advantage of not depending on the execution more or less imperfect of an instrument, and of being applicable to considerable trains of waggons, as we shall presently apply it.

SECT. IV. *Experiments on the friction of waggons.*

According to this principle, experiments were undertaken on one of the inclined planes of the Liverpool and Manchester Railway in the following manner.

From a point taken on the *Sutton* inclined plane, at 50 chains or 3300 feet from the base of that plane, were measured 34 distances of 10 chains or 330 feet each. At each of these points was set up a staff numbered, and its level accurately taken. The following are the admeasurements of the levelling, expressed in feet and decimals of feet.

The staves have since been replaced by permanent posts, which are distinguished, by red marks, from those which serve to indicate the miles of the road.

Numbers of the posts.	Total distance from the 1st post, in feet.	Total fall below the 1st post, in feet and decimals of feet.	
	feet.	feet.	Point of starting.
0	0	0	
1	330	3·47	
2	660	7·07	
3	990	10·62	
4	1320	14·36	
5	1650	18·17	
6	1980	21·77	
7	2310	25·53	
8	2640	28·98	
9	2970	32·07	Foot of the inclined plane, or rather middle of the curve.
10	3300	34·61	
11	3630	35·06	
12	3960	35·19	
13	4290	35·23	
14	4620	35·37	
15	4950	35·71	
16	5280	36·17	
17	5610	36·44	
18	5940	36·66	
19	6270	36·80	
20	6600	36·92	
21	6930	37·06	
22	7260	37·14	
23	7590	37·22	
24	7920	37·37	
25	8250	37·34	
26	8580	37·63	
27	8910	37·92	
28	9240	38·14	
29	9570	38·35	
30	9900	38·54	
31	10230	38·67	
32	10560	38·77	
33	10890	38·92	
34	11220	39·08	

On the ground where these experiments were made, a little beyond the foot of the inclined plane,

the waggons had to cross three junction roads, each of which required the passing over three switches. This made in all nine switches, either on one side of the rails or on the other. On passing over each of these obstacles, the waggons received a jolt from the unevenness of the road, and must have been retarded in their progress. The ground, therefore, is not favourable to the experiments, and tends to include in the friction the inevitable imperfections of the road.

The waggons employed in the experiments are of the following construction. They consist of a single platform supported on four springs; the wheels are 3 feet in diameter, and are fixed to the axle-tree, which turns with them; the body of the carriage rests upon the axle-trees, but outside of the wheels; that is to say, that the axles are prolonged through the nave in order to support the carriage. At the bearing they are turned down to $1\frac{3}{4}$ inches in diameter. By this disposition the body of the axle-tree preserves its usual strength to resist the shocks received by the wheels in the motion, and the bearing may at the same time be reduced to the slender diameter of $1\frac{3}{4}$ inches, because that part has nothing but the body of the waggon to sustain. The chair is armed with a piece of copper at its rubbing point on the axle, and the grease, placed in a small cast-iron box above the axle, runs on it slowly, but without interruption, during the whole of the motion. This

grease-box, filled every morning, is sufficient for the need of the whole day. In the experiments no alteration whatever was made in these dispositions, every thing being left the same as it is in the daily work, both with regard to the waggons and to the rails. Among the waggons there are some, the axle-bearings of which, instead of being from one end to the other of a uniform diameter of $1\frac{3}{4}$ inches, are thickened near the frame of the carriage by $\frac{3}{8}$ inch, and are, on the contrary, diminished as much at the other end. The axle-bearing thus consists of three cylindrical parts equal in length, and the diameters of which are $2\frac{1}{8}$, $1\frac{3}{4}$, and $1\frac{3}{8}$ inches.

The object of this disposition is to leave the mean diameter of the axle-bearing the same as before, but to transfer, however, the greatest force to the point which seems to suffer the most. These axles, few in number, are but an essay of which experience has not yet confirmed the advantage.

As all the experiments we are about to report have been made in a manner perfectly similar, we shall give the details merely of one of them, and shall afterwards collect in a Table the results which all have produced, with the elements of the calculation for each of them.

On the 1st of August, 1834, 24 loaded waggons taken indiscriminately, were conveyed to the ground of the experiments by the engine Atlas. The weight of the 24 waggons, taken accurately with their load,

amounted to 104·50 tons, and that of the tender-carriage of the engine, which remained attached to the waggons, was 5·50 tons, forming altogether an assemblage of 25 carriages, weighing 110 tons.

The middle carriage of the train being placed on the plane precisely opposite the starting point or post No. 0, and the engine being removed previously, the brakes were taken off at once at a signal given, and the 25 waggons committed to gravity on the plane. They continued their motion to 108 feet beyond the post No. 32, having thus traversed on the first plane a distance of 3300 feet with a vertical fall of 34·61 feet, and on the second a distance of 7368 feet with a fall of 4·21 feet. In this experiment then we have:

$$l' = 3300,\ h' = 34{\cdot}61,\ l'' = 7368,\ h'' = 4{\cdot}21.$$

We have just seen, besides, that the weight of the train was

$$P + p = 110\ t, \text{ or in lbs. } P + p = 110 \times 2240 \text{ lbs.}$$

It is also known that the quantity e, which appears in the equations, and which expresses the base of the hyperbolic logarithms, has for its value

$$e = 2{\cdot}71828\,;$$

and that the gravity g, expressed in English feet per second, is

$$g = 33 \text{ feet.}$$

Finally, the resistance of the air per square foot of

surface, at the velocity of 1 foot per second, is expressed, as we have seen, for $\epsilon = 1{\cdot}05$, by

$$Q = {\cdot}00125;$$

and the resisting surface of the train, measured as has been explained in the preceding chapter, viz., at 70 square feet for the transverse section of the train and 10 square feet per waggon, amounted in all to 320 square feet.

Nothing remains then, in order to have all the elements of the calculation, but to determine the value of the quantity n, viz.

$$n = \frac{p}{P+p} \cdot \frac{k^2}{R^2}.$$

This determination is easy; for p is the weight of all the wheels with their axle-trees, or as many times ·85 ton as there are carriages, and $P+p$ is known. Moreover, considering the wheel as a full cylinder, in which the weight of the axle should compensate for the void existing between the spokes, we should have approximatively, from the theoretical determination of momenta inertiæ,

$$\frac{k^2}{R^2} = {\cdot}50;$$

but some experiments made on axles separated from the carriage, with a view to determine precisely their centre of oscillation, having given for that fraction the number ·54, we will adopt that value. We shall have then

$$\frac{k^2}{R^2} = \cdot 54 ;$$

and consequently the expression of the quantity n will here become

$$n = \cdot 54 \times \frac{25 \times \cdot 85}{110} = \cdot 104.$$

These various values being substituted in the expression of Y, give

$$Y = 1 \cdot 7040 ;$$

and consequently the friction is

$$f = \cdot 002635 \text{ or } 5 \cdot 90 \text{ lbs. per ton.}$$

The calculations relative to the other experiments are performed in a manner entirely similar. Only, in three of them, to wit, the experiments VIII. IX. and X., which, besides the waggons, included also an engine, the value of f was first found, as before, and the friction of the whole train was concluded from it. But it was not till after having subtracted the friction proper to the engine itself, in consequence of a special experiment made immediately before and on the same spot, that the remainder was divided by the weight of the train, exclusive of the engine; and thus was obtained the friction per ton proper to the waggons. The special experiment here noticed, and from which we derive the friction proper to the engine, at the moment of the observation, will be reported further on.

In the experiments V. and IX. the train could

not be made to start precisely from the post No. 0, and the vertical fall and distance traversed varied in consequence; but account has been carefully taken of this in the calculation, as may be remarked in the Table.

During all these experiments the weather was fine and calm, and, as has already been said, nothing had been changed in the ordinary state of the waggons or the rails.

Experiments on the friction of waggons.

Number of the experiment.	Date of the experiment.	Designation of the train.	Weight of the train.	Effective surface presented to the shock of the air.	Height of fall on the first plane.	Distance traversed on the first plane.	Height of fall on the second plane.	Distance traversed on the second plane.	Total friction of the train.	Friction per ton.	Observations.
			tons.	sq. feet.	feet.	feet.	feet.	feet.	lbs.	lbs.	
I.	Aug. 3, 1836.	5 waggons of goods . . .	23·28	130	34·61	3300	3·10	5376	137	5·90	
II.	July 29, 1834.	5 waggons loaded with bricks	31·31	105	34·61	3300	3·94	6625	192	6·13	
III.	July 29, 1834.	5 waggons loaded with bricks	25·58	98	34·61	3300	3·58	6024	163	6·37	1 axle-box hot.
IV.	July 30, 1834.	19 waggons of goods . . .	92·00	260	34·61	3300	4·24	7428	542	5·89	
V.	July 31, 1834.	14 waggons of goods . . .	61·65	200	31·39	2994	3·93	6585	370	6·00	
VI.	Aug. 1, 1834.	10 wag. of goods and 1 tender	48·72	180	34·61	3300	3·97	6708	287	5·90	
VII.	Aug. 1, 1834.	24 wag. of goods and 1 tender	110·00	320	34·61	3300	4·21	7368	649	5·90	
VIII.	Aug. 2, 1834.	17 waggons, 1 tender, and the engine *Fury*, (friction 82·66 lbs., weight 8·20 tons, not included in that of the train)	86·76	260	34·61	3300	4·49	7962	443	5·11	
IX.	Aug. 2, 1834.	20 waggons, 1 tender, and the engine *Vulcan*, (friction 100 lbs., weight 8·34 tons, not included in that of the train)	101·80	290	34·41	3282	4·34	7629	543	5·33	
X.	Aug. 15, 1834.	7 waggons, 1 tender, and the engine *Leeds*, (friction 83 lbs., weight 7·07 lbs., not included in that of the train)	33·52	160	34·61	3300	2·74	4875	214	6·38	
		131 carriages	614·62						3540	5·76	

From these experiments, the mean friction of the waggons, taken independently of the resistance of the air, amounts to $\frac{1}{389}$ of the gross weight of the waggons, or to 5·76 lbs. per ton; but to simplify the calculations, we will take it at 6 lbs. per ton, which makes $\frac{1}{373}$ of the weight of the waggons.

These are the results which ought to be used, when, for the resistance of the air, the determination deduced from the most recent and most exact experiments on the subject is used, and when account is taken, as it ought to be, of the length of the prism formed by the train in motion, as well as of the effects of the air against the rotation of the wheels and the accessory parts of the waggons. But if the calculation were limited to the use of the determination of Borda, which does not enter into the consideration of the diminution of resistance of lengthened bodies, and if account were taken only, as is the custom, of the resistance of the air against the front surface, or transverse section, of the train; that is to say, if the calculation of the foregoing experiments were performed anew, with Borda's datum, and giving to Σ the value indicated by the waggon of greatest section, then it would be found that the friction of the waggons should be taken at 7 lbs. per ton.

It appears then, from this result, that for the mean velocity of the trains during the experiments, it would be indifferent to compute the friction of the waggons at 5·76 lbs. per ton, taking account of

the real resistance of the air and of its effects against the accessory parts noticed above, or to take the friction of the waggons at 7 lbs. per ton, accounting merely, according to Borda, for the resistance of the air against the waggon of greatest section. On the other hand, as, during the work of the engines, their velocity is so much the greater as the train they draw is less considerable, whence the resistance of the air increases as the friction of the train diminishes, it will equally be found that either of the two preceding calculations leads to very nearly the same result, for the total resistance opposed by the moving train, and that it is only in cases of extreme velocity that the two modes of calculation present a notable difference.

Without any important error then, the second of the two modes of calculation may be used. It is that which we had indicated in a former work (*Theory of the Steam Engine*), when unacquainted with any other researches on the resistance of the air than those of Borda; but now that M. Thibault's experiments have enabled us to employ a method much more exact, we have duly given it the preference, remarking at the same time that the definitive results of the calculations will not thereby be notably changed.

This satisfaction, however, attends the coincidence which we have just noted, viz., that an error in the valuation of one of the two elements of the total

resistance of the trains, would cause no important error in the calculation of the effects of the engines.

SECT. V. *Of the causes of variation in the friction of carriages.*

In the preceding experiments we employed as much as possible trains composed of a great number of carriages, because there often exist great differences between the individual frictions of two waggons of similar construction, and that it is only by uniting them in numerous trains, that the compensation which establishes itself between their different frictions can lead to a uniform mean result.

We must add, moreover, that the determination of the friction, which we have just obtained, refers to the waggons whose construction has been indicated above, and to the state of the Manchester and Liverpool Railway. As, however, on other lines, different circumstances may occur, it becomes necessary to notice here the variations which may result from them in the friction of the carriages.

The causes of the variation of friction are of four kinds: 1. the construction, the maintaining, and greasing of the carriage; 2. the state of the rails; 3. the diameter of the axle-bearing and that of the wheel; and, 4. the proportion between the total weight of the carriage and that of the body of the carriage taken separately.

That the influence of these four causes may be quite clear, we will refer to what has been said in sect. III. of this chapter. It was there seen that the friction of a carriage consists of two parts: one owing to the friction of the axle, which depends only on the weight of the body of the carriage; and the other owing to the rolling of the wheel on the rail, which depends on the total weight of the carriage. It has been seen that the first of these frictions produced against the motion a force which we have represented by

$$f' P \frac{r}{R},$$

and the second a force represented by

$$f'' (P+p) \frac{1}{R},$$

f' denoting the coefficient of the friction of axles, f'' that of the rolling friction, r the radius of the axle-bearing, and R that of the wheel. But in order to simplify, we have replaced the two expressions by a single one, making

$$f' P \frac{r}{R} + f''(P+p) \frac{1}{R} = f (P+p);$$

that is to say, instead of entering into the consideration of these two separate frictions, we have been content to consider the single force resulting from their union, and which we have supposed proportional to the total weight $(P+p)$ of the carriage.

But it is now requisite to direct a moment's attention to this expression.

1st. Since the quantity f' expresses the friction of the axle on its chair, for a given weight of the body of the carriage, it is plain that the more carefully rounded, polished, and greased the axle is, and the more easily the metals in contact slide upon one another, the less the coefficient f' will be. On this first term, then, is felt the influence of the mode of construction and greasing of the carriage.

2d. From the same motive, the influence of the state of the rails and of the perfect roundness of the wheels is felt on the factor f'', which expresses the coefficient of the rolling friction.

3d. The smaller the diameter $2r$ of the axle-bearing, the more the first term, or resistance due to the friction of the axle, will be diminished; and similarly, the more the diameter 2R of the wheel shall be augmented, the more thereby will be diminished the two partial frictions which take place, either on the axle or on the rail.

4th. Finally, between two carriages wherein all the preceding conditions were strictly identical, some difference might yet arise in the value of the definitive friction f. In effect, the preceding relation giving

$$f=f'\frac{\mathrm{P}}{\mathrm{P}+p}\cdot\frac{r}{\mathrm{R}}+f''\frac{1}{\mathrm{R}},$$

it is visible that the invariability of the quantities f', f'', r and R will not prevent a variation in the value

of f, according to the magnitude of the fraction $\frac{P}{P+p}$, that is to say, according to the ratio between the weight of the body of the carriage and the total weight of the waggon.

From these divers observations, it becomes clear that on the same railway, the definitive friction f, of which we have found above the mean value 6 lbs. per ton, may vary according to the state of the waggons, the state of the rails, and the proportion of the load to the weight of the carriage; and that between carriages differently constructed, the friction may vary yet again, according to the diameter of the axle-bearings and of the wheels.

The preceding considerations show that the valuation of the friction, which we obtained above, ought to be understood only of carriages similar to those which were submitted to experiment, and subject to like conditions, viz. with iron axles, turning on brass chairs and provided with self-acting grease-boxes; with three-feet wheels and axle-bearings $1\frac{3}{4}$ inches; with the use of a well-kept railway, and finally with the usual proportion of about $\frac{5}{6}$ between the weight of the body of the loaded carriage and the total weight of the waggon. Were these conditions materially altered, a new determination of the friction would become necessary.

CHAPTER VI.

OF GRAVITY ON INCLINED PLANES.

We have seen, in the preceding chapter, how the resistance caused on a railway by the friction of the waggons may be valued. But it sometimes happens that this friction is the smallest part of the total resistance which the engine has to overcome, in order to effect the motion of the train. This case occurs when the way is not level, and the train is obliged to ascend an acclivity. The resistance then caused is, as every one knows, much greater than on a level line, and in consequence it becomes necessary to take account of it in the calculations.

When a body is placed on an inclined plane, the weight which urges it, and which always acts in a vertical line, is decomposed into two forces: one perpendicular to the plane, and which measures the pressure produced against the plane, by virtue of the weight of the moving body, and the other parallel to the plane, and which tends to make the body slide or roll along the declivity. The latter force, which we will call *the gravity* along the plane, would inevitably drag the body towards the foot of the declivity, were it not counteracted by a con-

trary force. When therefore a train of waggons has to ascend an inclined plane, the moving power must apply to it: firstly, a force able to overcome the friction of the waggons themselves; and again, another force able to overcome the gravity in the direction of the plane. If, on the contrary, the mover draw the train of waggons down the plane, then, in order to produce the motion, it will evidently have to apply only a force equal to the difference between the friction proper to the waggons and the gravity, since the latter force then acts in the same direction as the mover.

When a body of a given weight is set on a plane of a given inclination, we know that, in order to obtain the gravity of the body along the plane, its weight is to be multiplied by the fraction which expresses *practically* the inclination of the plane. Thus, for instance, on a plane inclined $\frac{1}{89}$, that is to say, on a plane which rises 1 foot on a length of 89 feet measured along the acclivity, the gravity of 1 ton, or 2240 lbs., is

$$\frac{2240}{89} = 25{\cdot}2 \text{ lbs.}$$

Moreover, when a train of waggons ascends an acclivity, the engine has not only to surmount the gravity of the waggons of the train, but likewise its own gravity and that of the tender which follows it; and these forces do not present themselves when the motion takes place on a horizontal line. It is then

on the *total* weight of the train, that is, including engine and tender, that the resistance caused by gravity on acclivities is to be calculated.

If it be supposed, for instance, that a train of 40 tons, tender included, be drawn up a plane inclined $\frac{1}{89}$, by an engine weighing 10 tons, it is clear that the definitive resistance opposed to the motion by the train will be

40×6 lbs. $= 240$ lbs., friction of the carriages at 6 lbs. per ton . . .	240 lbs.
$50 \times \frac{2240}{89} = 1258$ lbs., gravity of the 50 tons of the train (reduced to lbs.) on a plane inclined $\frac{1}{89}$, to be added	1258
Total resistance arising from friction and gravity	1498 lbs.

If, on the contrary, the same train had to descend a plane inclined $\frac{1}{1000}$, the resistance it would then offer would be

40×6 lbs. $= 240$ lbs., friction of the waggons	240 lbs.
$50 \times \frac{2240}{1000} = 112$ lbs., gravity of the train, to be deducted	112
Definitive resistance arising from friction and gravity	128 lbs.

In general, let M be the weight of the train, in tons gross and including the tender; let *m* be the

weight of the engine, expressed also in tons; k the friction of the waggons per ton, expressed in lbs., as has been explained in the preceding chapter; finally, let g be the gravity, in lbs., of 1 ton on the plane in question. It is clear in the first place, from what has been said above, that the quantity g will be equal to 2240, multiplied by the practical inclination of the plane; so that if $\frac{1}{e}$ express that inclination, or the ratio of the height of the plane to its length, we shall have, to determine g, the equation

$$g = \frac{2240}{e}.$$

This premised, the friction of the waggons will have for its value

$$k\mathrm{M}.$$

Again, since g expresses the gravity of 1 ton, it is plain that

$$g\ (\mathrm{M} + m)$$

will represent, in lbs., the gravity of the total mass, train and engine, placed on the inclined plane.

Thus, according as the motion takes place in ascending or in descending, the total resistance, in lbs., offered by the train on the inclined plane, will be

$$k\mathrm{M} \pm g\ (\mathrm{M} + m) = (k \pm g)\ \mathrm{M} \pm gm,$$

an expression in which the sign + belongs to the ascending motion, and the sign — to the descending motion, of the train.

It will always be easy then to obtain the number of lbs., which represents the resistance opposed by a train in motion on a plane of a given inclination. This is the only result which we want at this moment; but as the intervening of inclined planes on railways brings with it some particular considerations, we will return to this subject further on, in order to solve the various problems that may occur.

We have said above that when a body is placed on an inclined plane, its weight is decomposed into two forces, one acting along the declivity, as has been explained, and the other acting normally to the plane, and measuring the pressure which the weight of the body produces on the plane. In this case then, the weight of the train, with reference to the sustaining plane, is now expressed only by the normal component just mentioned, and not by the total weight of the waggons. Consequently, to be thoroughly accurate, instead of then reckoning the friction of the waggons from their total weight, it ought to be reckoned only from the normal component on the plane. This force is to the weight of the waggons, as the horizontal length of the inclined plane is to its length measured along the declivity. But as there never occur, on railways, planes so much inclined as to render the difference between those two lines not wholly inconsiderable, it is perfectly useless to make a distinction on that head.

For instance, on a plane whose practical inclination shall be $\frac{1}{100}$, which is a steep ascent for a rail-

way, we find by geometry that the horizontal length of the inclined plane will be to its length measured along the declivity, in the ratio of the numbers

$$\frac{99995}{100000}.$$

The difference then between the absolute and the relative weights of the waggons, is always an inappreciable quantity in practice. For this reason, in all cases, we shall reckon the friction of the waggons placed on inclined planes, at the same rate as if they were placed on a level line.

CHAPTER VII.

OF THE PRESSURE PRODUCED ON THE PISTON BY THE ACTION OF THE BLAST-PIPE.

SECT. I. *Of the effects of the Blast-pipe.*

WE have just examined and measured successively several of the resistances which are opposed to the engine in its motion, viz., that of the waggons along the rails, and that of the air against the trains. But among other resistances which the piston has yet to overcome, is one arising from the disposition of the engine itself, and of which it will be proper to treat before proceeding further.

The steam, after having exerted its action in the cylinder, might escape into the atmosphere by a large opening. It would then be possible for it entirely to dissipate itself in the air, during the time the piston takes to change its direction. Consequently the steam would in nowise impede the retrograde motion of the piston, whatever might be the velocity of the piston. But the disposition adopted is contrary to this. The steam, on leaving the cylinder, has no other issue towards the atmosphere than an aperture exceedingly narrow; nor can it, by that aperture, escape totally within the time of

one stroke, except by assuming a very considerable velocity in its motion. For this, the steam in the cylinder must necessarily be at a pressure sensibly greater than that of the atmosphere into which it flows; and as the pressure of the steam while flowing acts in all directions, and consequently against the piston, it results that the latter, instead of having simply to counteract the atmospheric pressure, finds an additional one to overcome, which is to be added to the divers resistances already measured.

This new cause of resistance might, as has been said, be in a great measure suppressed, by enlarging sufficiently the outlèt of the steam. But to do this would be to lose one of the most active causes of the definitive effect of the engine; for the object of the disposition of which we treat is to excite the fire sufficiently, and to produce, in a boiler of small dimensions, the very great quantity of steam requisite for the rapid motion of the engine. To this end, the waste steam is conducted to the chimney, and thrown into it by intermittent jets, through a blast-pipe or contracted tube, placed in the centre of the chimney and directed upwards. The jet of steam, as it rushes with force from this aperture, rapidly expels the gases which occupied the chimney. It, consequently, leaves behind it a vacuum; and this is immediately filled by a mass of air rushing through the fire-grate into the space where the vacuum has been made. At every aspiration thus produced, the fuel contained in the fire-box grows

white with incandescence. The effect then is similar to that of a bellows continually urging the fire; and the artificial current created in the fire-box by this means is of such efficacy for the vaporization, that were the blast-pipe suppressed, the engine would become almost useless, which proves that the current of air attributable to the ordinary draught of the chimney is in comparison but very trifling.

We shall return in the sequel, when speaking of the vaporization of the engines, to the effects of the blast-pipe relative to the production of steam. At present we have only to consider its effects relative to the pressure it causes against the piston.

For this purpose we must first examine how this pressure, necessary to the outflow of the steam, is produced in the cylinder. At that moment when the eduction-pipe opens, and the steam begins to escape into the atmosphere, its pressure is yet the same as it was immediately before, when it served as the motive force to produce the motion. The latter pressure then is that which takes place at the first moment, and which, by reason of its excess above the atmospheric pressure, produces the efflux of the steam. But as that pressure is very considerable, and as the gases acquire, as is well known, very great velocities, even under very weak motive or effective pressures, it follows that at this moment the steam necessarily rushes from the cylinder with an enormous velocity; and as, moreover, its density is then very considerable, it results that the greater

part of the steam escapes immediately, or at least in a very short space of time. However, as the efflux takes place, the pressure of the remaining steam diminishes, as well as its density. Consequently the issuing velocity of the steam and the quantity of it which flows out in a given time diminish at the same time. A point then occurs at which the spontaneous efflux of the steam by the blast-pipe no longer exceeds the velocity which, by reason of the size of the orifice, corresponds to the velocity of the piston in the cylinder. Beyond this point the issuing velocity of the steam cannot diminish, for the piston, continuing its stroke, forces it out of the cylinder as rapidly as itself performs its motion. It is then the velocity of the piston which fixes the lower limit of the velocity of efflux of the steam; and consequently the smallest effective pressure that can take place in the cylinder is that which is capable of producing, in the efflux of the steam by the blast-pipe, a velocity corresponding to that of the piston.

Thus, at the moment of the opening of the eduction-pipe, there is a tendency to produce in the blast-pipe an effective pressure equal to that which the steam had during its motive action in the cylinder; but the duration of this extreme pressure is in a manner instantaneous. It immediately diminishes rapidly, and soon attains its inferior limit, which afterwards subsists till the end of the stroke; and then is produced in the blast-pipe a

uniform effective pressure, corresponding to a velocity of efflux of the steam measured by the velocity of the piston.

Again, as the two cylinders communicate with a single blast-pipe, it happens that each cylinder transmits to the blast-pipe alternately steam, first at a very high pressure, and then at a low one; and these effects succeed each other in such sort, that when one cylinder supplies steam at a low pressure, the other on the contrary gives it at the higher pressure. As these alternations are exceedingly rapid, there must result in the blast-pipe a certain mean pressure, which forms in a manner a factitious atmosphere, in which the two pistons work. This factitious atmosphere it is necessary to know; for evidently as soon as it becomes known, it will suffice to substitute it, in the calculation, for the natural atmosphere, to take account, without any other difficulty, of the resistance exerted against the piston by the action of the blast-pipe.

Before proceeding further, we will therefore examine how this mean pressure existing in the blast-pipe, must be modified according to the different circumstances of the working of the engine.

1st. If the velocity of the piston increases, without any other change being made in the engine, it is visible, from what has been said above, that the lower limit of the effective pressure in the blast-pipe will increase; and according to the principles admitted in the flowing of fluids, it will increase

nearly as the square of the velocity of the piston. But on the other hand, it will be seen further on, that with the same vaporization in the boiler, the velocity of the piston cannot increase, without the effective pressure in the cylinder diminishing nearly in the inverse ratio of that velocity. Hence, in the case before us, namely, that of an increase of velocity of the engine without an increase of vaporization, the inferior limit of the effective pressure in the blast-pipe will augment in proportion to the square of the velocity of the piston, and its superior limit will diminish in the inverse ratio of the same velocity. As we have seen besides, that the maximum pressure in the blast-pipe is of a duration much less than the minimum pressure, it follows definitively that the mean effective pressure in the blast-pipe will receive an augmentation, simultaneous and in a certain proportion with the velocity of the piston.

2d. If, the velocity of the piston remaining the same, the vaporization of the boiler increase, it is plain that the velocity of the piston can then remain constant, only because the steam arrives in the cylinder with a total pressure augmented nearly in the ratio of the vaporization, or with an effective pressure augmented in a manner corresponding to it. It is now therefore the superior limit of the effective pressure in the blast-pipe, which will have an increase correspondent to the vaporization produced, whereas the lower limit of the same pressure

being always indicated by the velocity of the piston, will on the contrary undergo no change. Thus, in this second case, the mean effective pressure in the blast-pipe must necessarily increase in a certain ratio with the vaporization of the boiler.

3d. Finally, if the velocity of the piston remain the same, as well as the vaporization of the boiler, but if the orifice of the blast-pipe be diminished without altering the area of the cylinder, it is clear that the same velocity of the piston will then correspond to an issuing velocity of steam by so much the greater; and that if, for instance, the area of the blast-pipe be reduced to the half of what it was before, the issuing velocity of the steam, corresponding to the velocity of the piston, will be doubled. But, from the principles of the efflux of fluids, this double velocity will require a motive or effective pressure nearly quadruple. Hence, in this case, the inferior limit of the effective pressure in the blast-pipe will vary nearly in the inverse ratio of the square of the orifice of efflux of the steam; but the superior limit of the same pressure will not vary, since it is always fixed by the pressure of the steam during its action in the cylinder. Therefore, definitively in this third case, the mean effective pressure in the blast-pipe will receive an augmentation increasing in a certain inverse proportion of the orifice of the blast-pipe.

These divers effects would no doubt be susceptible of a solution more or less exact by calculation; but

considering their nicety and at the same time the imperfectness of the theory of the efflux of fluids, we deem it more useful for the applications, to endeavour to determine them in a direct manner and by observation. For this reason, we shall make use of the preceding considerations, only to guide us in the research of the laws which may be derived from experience in this respect.

We will nevertheless observe, that there is a moment when the pressure in the blast-pipe produces no opposition against the motion of the piston. This effect depends on the circumstance that, from a disposition of the engine which we shall explain in speaking of the lead of the slide, the eduction-port of the steam is opened a little before the piston has reached the bottom of the cylinder. The result is, that during the short interval yet left for the piston to traverse to finish its stroke, the pressure in the blast-pipe is found acting in the direction of the motion, instead of acting against it. But as, nearly at the same moment and from the same disposition, the steam of the boiler comes in beforehand against the motion of the piston, it follows that the resistance owing to the blast-pipe is only replaced by a stronger resistance. As however the velocity of the piston is then nearly null, and as its action to produce the motion is equally without efficacy, we will admit that the one effect replaces the other, and shall enter on no distinction in that respect.

Sect. II. *Experiments on the resistance produced against the piston by the action of the Blast-pipe.*

To measure the resistance produced against the piston by the action of the blast-pipe, and the modifications it undergoes according to the circumstances in which the engine works, we undertook a series of experiments, which we are about to describe.

The blast-pipe of the engine Star being taken out of the chimney, the extremity of it was cut at the point where the cone was three inches in diameter, and the removed part was replaced by a bonnet conical at the bottom, and which was fitted at this point with screws on the remaining portion of the cone of the blast-pipe (fig. 36). At its upper part, this bonnet changed into a quadrangular conduit *aabb*, each side of which was two inches and a half in width, measured in the inside. Of the four sides of this conduit, three were fixed, and perfectly smooth on their inner surface; the fourth *aa* was moveable on a hinge *c*, and when pushed at *a′a′*, towards the inside of the passage, in which it moved with an easy friction, the steam-way became narrowed by so much. Thus, when this factitious blast-pipe was entirely open, it presented a square orifice whose side was 2·5 inches, that is to say, an area of 6·25 square inches; and when the moveable side was forced into the opening 1½ inches, the efflux orifice was no more than 2·5 inches by 1

inch, that is to say, was reduced to 2·5 square inches of area. By this means, then, the orifice of the blast-pipe could be altered at pleasure.

In order to execute this change easily, without opening the chimney or stopping the engine, a rod M′O, fixed on the moveable side of the blast-pipe, communicated, by means of a lever MOQ, whose fixed point was at Q, with a long rod M*m*, whose other extremity *m* reached to the engine-man's stand. This rod M*m* was composed of two parts: one, ME, terminated by a nut E invariably fixed to the rod; and the other, *m e*, terminated, on the contrary, by screw-bolts which inserted themselves into the nut, and thus united the two pieces into one. The part *m e* of this rod passed into a fork PN, where it was maintained by two collars, to prevent its sliding longitudinally. It then terminated by a crank handle T. When a certain number of turns were made with this handle, it is plain that the screw *e* was made to penetrate more or less into the nut E, and that, consequently, the rod *m*M was shortened or lengthened. Thus, as the point N was fixed, it is evident that the moveable side of the blast-pipe was by so much either drawn in or pushed out.

To measure precisely these shortenings or lengthenings of the rod, a fixed index *i* was attached to the steam-dome of the boiler, and the upper surface of the nut E was marked with divisions. When therefore, by the motion of the handle, the nut

approached the fork N, its divisions passed successively under the fixed index; and consequently the addition to the length of the rod might be read immediately. The dimensions of the divers pieces were such, that this increase of length indicated precisely the contraction that had taken place in the blast-pipe.

In order to obtain the pressure of the steam after it had left the cylinder, a brass tube of half an inch in diameter, inserted into the pipe leading to the blast-pipe, brought a portion of that steam into a receiver, placed on the engine-man's stand. This tube, on leaving the compartment of the chimney, was protected against the effects of the external refrigeration of the air, by a thick covering of hemp carefully put on and defended by a coat of paint. The receiver into which the steam was conducted was 12 inches high and 3 inches in diameter. It bore three instruments adapted to measure the pressure, viz., an air-gauge, a thermometer, and a little syphon-manometer. The syphon-manometer had the inconvenience of filling with water, and was in consequence abandoned; but during all the observations which were made with the three instruments their indications accorded exactly. Only, after the stoppages of the engine, the thermometer-gauge was much longer than the other two in marking the pressure.

The whole of this apparatus is seen represented in fig. 24 (Pl. V). VV is the tube which brings

the steam from the blast-pipe to the receiver; A is the receiver, closed at its upper part by a safety-valve maintained in its place by the pressure of an ordinary spring-balance F; B is the air-gauge, and *r* is the cock by which the steam arrived from the interior of the receiver to the ball of the instrument. C is the thermometer or thermometer-gauge; *dd* is the tube which conducted the steam from the receiver to the little syphon-manometer, which could not be figured for want of room. In fine, the discharging cock R, seen at the bottom of the receiver, served to let out the water which formed therein by condensation at the commencement of the experiments and till the mass of the system had acquired a proper temperature. The apparatus once sufficiently heated, this cock, when opened, let out nothing but a jet of perfectly transparent steam, and never any water, which proved that no condensation of steam was taking place in the receiver.

The steam was taken at the point where the pipes proceeding from each cylinder unite to form the origin of the blast-pipe. At this point the pressure was successively that of the two cylinders. Consequently the rapidity of the alternations of the pistons maintained there a mean constant pressure, at least as long as no variation occurred in the circumstances which we shall presently speak of. At the moment of the starting of the engine, when the velocity was but 2 or 3 miles per hour, the mercury, at every stroke of the piston, was seen to rise sud-

denly, in the air-gauge and in the syphon-manometer, to a height corresponding to about 1 lb. of effective pressure per square inch. But this effect was produced and destroyed instantaneously, so that in the duration of one stroke, the space of time wherein the pressure was null was greater than that in which it was 1 lb. above the atmospheric pressure. Afterwards, as the velocity of the engine increased, the mercury rose permanently in the manometers, and its oscillations of level became less and less sensible. At the velocity of 16 to 18 miles an hour a very slight motion was still discernible in the surface of the mercury at every stroke of the piston; but beyond that point the oscillations became insensible, and the pressure was no longer seen to vary but with the circumstances which formed the object of the experiments.

The apparatus being fixed on the engine, when, during the motion, the orifice of the blast-pipe was contracted, it immediately caused the pressure to rise in the manometers several pounds, according to the contraction made in the aperture, and on bringing back the blast-pipe to its former dimensions the pressure returned to the same point as before. Similarly, as the velocity of the engine increased or diminished, the pressure in the blast-pipe was seen to vary in a corresponding manner. And finally, whenever, by putting coke on the fire or water in the boiler, the vaporization of the boiler

was temporarily diminished, the pressure in the blast-pipe was instantly seen to lower, and to resume its former degree only when the vaporization had resumed its ordinary activity. There remained no doubt then that the velocity of the engine, the rate of vaporization, and the orifice of efflux of the steam, had an immediate effect on the pressure in the blast-pipe. As to the pressure in the boiler, since the steam, before arriving at the blast-pipe, passed first through the cylinder, it is clear that the pressure in the boiler could not have modified the pressure in the blast-pipe, but by first modifying that of the cylinder. Now we shall hereafter show that this latter effect, from the boiler to the cylinder, does not exist; neither then could it exist from the boiler to the blast-pipe. And, in fact, we observed that the augmentation of pressure in the boiler was, according to the circumstances, attended at times with an elevation, at other times with a diminution of pressure in the blast-pipe, as may besides have been remarked already in the experiments related in Section VI. Chapter II.

Of the three circumstances just mentioned, as modifying the effects of the blast-pipe, the first that we chose to submit to inquiry was the influence of the velocity of the engine on the pressure due to the blast-pipe. For this purpose, the fire being kept in the same state of intensity, and the boiler regularly fed with water, in order to preserve, as much as possible, a uniform vaporization, and the orifice of

the blast-pipe being maintained constant, we made the observations related in the following Table. We thereto add the last column, in which is inscribed the pressure which should have been observed, had the variation taken place exactly in proportion to the velocity.

To perform this calculation, we take as our point of departure, in each series of experiments, the pressure corresponding to the mean velocity of the motion.

We must, however, add here, that nothing is more difficult to obtain than uniformity in the vaporization of the engine. Every time that coke is thrown into the fire-box or water sent to the boiler, the production of steam is immediately reduced, though the velocity of the engine does not detect the change, on account of its acquired impulse; but the difference of vaporization is felt immediately in the receiver, where, as has been said, the manometers are seen to lower all at once and not to resume their usual degree till after a certain time. A contrary effect takes place when the supply of the fire and feeding of the boiler are momentarily suspended, which especially happens during ascents, because the engine-men are then apprehensive of diminishing the power of the engine too much. These circumstances oblige us, as the Table shows, to recur to the mean of the observations, in order to obtain the corresponding pressures and velocities.

We must equally give notice that in the two

series of experiments contained in the Table, the orifice of the blast-pipe was not the same.

Experiments to determine the influence of the velocity of the motion, on the pressure due to the blast-pipe.

Velocity of the engine in miles per hour.	Observed effective pressure, on the opposite face of the piston, in lbs. per sq. inch.	Mean velocity.	Mean effective pressure, by observation.	Effective pressure calculated, in the direct ratio of the velocity of the motion.
15·	4·	15·12	4·2	4·3
15·24	4·4			
16·55	4·9	16·55	4·9	4·7
16·95	4·3	17·08	4·9	4·8
17·21	5·6			
7·28	1·8	6·26	1·8	2·2
9·11	2·8	8·57	2·8	2·8
14·53	4·4	14·53	4·4	4·5
16·39	5·3			
16·67	5·8	16·67	5·3	5·2
16·96	4·8			
17·50	5·1	17·61	5·6	5·5
17·73	6·2			

We see by these results, that the effective pressure exerted against the piston, by the action of the blast-pipe, varies very nearly in the direct ratio of the velocity of the piston, or of the engine.

From the considerations which we have presented above, it still remained to seek according to what law the pressure on the piston, in the action of the blast-pipe, varies with the ratio of the vaporization in the boiler, to the area of the blast-pipe through which the steam is forced to flow. With this view

were undertaken the experiments which we shall presently offer, note being carefully taken in them, of the velocity of the engine, of the area of the blast-pipe, and finally of the vaporization of the boiler.

After having compared the observations among themselves, we find that the law to which they approach nearest is that of a simple proportionality to the ratio $\frac{S'}{o}$, in which S′ represents the *total* vaporization or the expenditure of water of the boiler, such as we observed it in the experiments, and o represents the area of the orifice of the blast-pipe. It is for this reason that we annex to the Table of the experiments, a last column containing the resistance against the piston created by the blast-pipe, such as calculation would give it, supposing that it were directly proportional to the velocity of the engine, and to the ratio of the total vaporization to the area of the blast-pipe, that is to say, supposing it to be of the form

$$Kv\frac{S'}{o}.$$

To obtain the coefficient K, which should serve to operate this reduction, we first compared the product $v\frac{S'}{o}$ to each of the results given by observation, and thence deduced the value of K, which was found to be ·0113. Consequently we calculate the last column by the formula

$$\cdot 0113\, v \frac{S'}{o}.$$

With regard to the observations of velocity and pressure inserted in the Table which we are about to present, we must notice that each of them is a mean taken on from ten to twenty consecutive observations, which by so much the more insures their accuracy. Nevertheless, as these observations were all made at the same period of the experiment, and at very short intervals of time from each other, it is still found, on looking over the results to discover the law which represents them, that the difficulty already mentioned, of maintaining the uniformity of the vaporization in the boiler, occasions from time to time anomalies not inconsiderable in the observations. But on recurring to a mean taken between observations made at two different periods of the experiments, those anomalies are found to disappear almost entirely; which is a proof that they arise solely from this, that the observed pressure in the blast-pipe results from the *momentary* vaporization of the engine, animated or slackened during that portion of the experiment, whereas the calculated pressure can be grounded only on the *mean* vaporization of the whole experiment.

The observations we have just made are relative to the last two columns of the Table. In that which contains the dimensions of the blast-pipe, instead of giving those dimensions in square inches, as resulted from the form of the blast-pipe employed,

we give the diameter of a round blast-pipe offering the same area of orifice. As the circular form is the only one in use, we thought that the Table presented in this manner, would become more commodious for practical applications.

Finally, we must yet add, that in the experiments about to be related, we have sometimes reduced the area of the orifice of the blast-pipe to but 2·50 and 3·125 square inches, and thence resulted, even for very moderate velocities, very great resistances against the piston. But such contractions are not in use: before the variable orifice which we have described was fitted up on the Star engine, the blast-pipe was of the diameter of 2⅜ inches, or 4·5 square inches of area, which is a measure usual enough in these engines. The blast-pipe then, in the regular use of it, produces only resistances proportioned to that dimension; and this remark is necessary, that the results related in the Table may not be regarded as mean data suitable to the regular work of locomotives.

Experiments on the resistance produced against the piston by the action of the blast-pipe.

Date of the experiment, and designation of the engine and its load, tender included.	Vaporization during the experiment, in cubic feet of water per hour.	Diameter of the blast-pipe.	Velocity of the engine, in miles per hour.	Effective pressure against the piston, observed during the experiment.	Effective pressure, calculated by the formula $\cdot0113\, v\, \frac{S'}{O}$.
1836.	cubic feet.	inches.	miles.	lbs. per sq. in.	lbs. per sq. in.
Aug. 9, *Star*, from Liverpool to Manchester, with 120·27 tons	67·71	1·995	16·95	4·3	4·1
			15·00	5·0 } 4	3·6 } 3·6
			15·00	3·0 }	3·6 }
			17·21	5·6	4·2
			15·24	4·4	3·7
			16·55	4·9	4·0
Aug. 9, *Star*, from Manchester to Liverpool, with 75·05 tons . .	68·79	1·995	16·96	4·8	4·2
			17·50	5·1	4·3
			14·53	4·4	3·6
			16·67	5·8	4·1
			16·39	5·3	4·1
			17·73	6·2	4·4
Aug. 9, *Star*, with 38·58 tns.	68·79	1·995	9·11	2·8	2·3
Aug. 9, *Star*, with 41·97 tns.	68·79	1·995	7·28	1·8	1·8
Aug. 9, *Star*, from Liverpl. to Manchr. with 96·30 tns.	60·64	2·821	22·85	3·0	2·4
			20·00	2·4	2·1
			20·00	2·3	2·1
			21·82	1·8	2·3
			17·56	2·3	1·9
			19·25	2·0	2·1
Aug. 10, *Star*, from Liverpool to Manchester, with 43·65 tons . . .	65·49	2·360	23·64	4·8 } 3·6	4·0 } 3·7
			20·00	2·4 }	3·4 }
			26·67	5·6 } 3·7	4·5 } 4·3
			25·00	1·8 }	4·2 }
			20·69	2·9	3·5
			20·77	2·2	3·5
Aug. 13, *Star*, from Liverpool to Manchester, with 109·68 tons . .	54·20	2·360	19·57	1·0	2·7
		1·995	13·33	2·4	2·6
			17·14	3·8	3·4
			10·29	2·1	2·0
			12·63	1·6	2·5
			12·47	1·2	2·5
Aug. 13, *Star*, from Manchester to Liverpool, with 48·48 tons . .	62·83	1·784	21·82	5·4	6·2
			23·53	5·0	6·7
			18·75	4·2	5·3
			19·20	3·4	5·5
			20·00	4·9 } 5·5	5·7
			20·00	6·0 }	5·7

Comparing the last column and the last but one of this Table, we recognise between them a sufficient coincidence for practical purposes. Consequently, in all cases wherein the resistance caused against the piston by the action of the blast-pipe shall not have been directly observed, it may be determined by the formula

$$\cdot 0113\, v\, \frac{S'}{o};$$

in which v is the velocity of the engine in miles per hour; S′ the *total* vaporization of the boiler in cubic feet of water per hour; o the area of the orifice of the blast-pipe expressed in square inches; and the result of the calculation will give the pressure in the blast-pipe expressed in pounds per square inch. The pressure per square foot will be 144 times as much.

With respect to the quantity represented here by S′, the experiment from which we deduced the formula shows, that the vaporization signified is the *total* vaporization effected in the boiler, that is to say, the vaporization counted before deduction of the water carried away in a liquid state with the steam. But as the engine Star makes habitually no waste of steam by the safety-valves, it is understood that in engines in which this loss does take place, it is not considered as included in the value of S′, and consequently, if a very nice accuracy be desired, it will be proper, first of all, to

subtract it from the vaporization effected, in order to obtain the quantity here expressed by S′.

Making in the preceding formula

$$\cdot 0113 \frac{S'}{o} = p',$$

the pressure in the blast-pipe may be represented by the expression

$$p' v,$$

in which p' will be the ratio of the vaporization to the orifice of the blast-pipe, multiplied by a constant coefficient.

Now, for engines which vaporize as much as 60 cubic feet of water per hour, practice has established the use of a blast-pipe of 2·25 inches diameter, or 3·96 square inches of area, which gives for the value of the ratio $\frac{S'}{o}$,

$$\frac{60}{3 \cdot 96} = 15 \cdot 2$$

In constructing engines of a greater vaporizing power, it would be natural to increase the area of the blast-pipe in proportion to the quantity of steam to which it is to give issue. There is room therefore to think that the proportion thus established between the production of steam and the area of the blast-pipe, will not be notably changed by the different engine-makers. Consequently the ratio $\frac{S'}{o}$ may be regarded approximatively as a constant quantity, given by the above proportion.

Then the preceding formula will be reduced simply to the expression

$$\cdot 175\, v,$$

which will be useful especially in valuing the pressure due to the blast-pipe in engines whose vaporization is unknown. In this formula, v is the velocity of the engine, in miles per hour, and the result is the pressure in the blast-pipe, expressed in pounds per square inch. As the pressure per square foot is 144 times as much, it follows that if we require the pressure expressed in that manner, as will be found necessary in the course of this work, we shall obtain its value by the formula

$$25 \cdot 2\, v.$$

We shall then represent generally the pressure in the blast-pipe under the form

$$p'\, v\,;$$

and for the most ordinary cases, it will suffice to give to p', in this expression, one of the constant values above mentioned, according to the measures employed. But if the engine in question should differ too considerably from the proportions which we have just indicated with reference to the area of the blast-pipe, it would be necessary to substitute for that approximate value of p', its value function of S' and o.

In fine, to dispense with all calculation on this head, we here subjoin a Table, in which will be found, on inspection, the pressures in the blast-pipe

for given circumstances, and we continue that Table beyond the actual effects of locomotive engines. It will there be recognised how, by augmenting the orifice of the blast-pipe, the resistance against the piston, arising from that cause, may be diminished at pleasure; and it may probably be found, in consequence, that in the regular work of locomotives, it might be useful to adopt a blast-pipe with a variable orifice, such as we employed temporarily in our experiments. Then, by contracting the orifice of efflux of the steam only just as much as is necessary, there will be no more resistance against the piston than what is indispensable for the proper action of the engine.

Practical Table of the pressures against the piston, due to the action of the blast-pipe.

Diameter of the blast-pipe.	Velocity of the engine, in miles per hour.	Effective pressure against the piston, in lbs. per square inch, the vaporisation of the boiler, in cubic feet of water per hour, being: 30	40	50	60	70	80	90	100
	miles.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.
2 inches.	5	0·5	0·7	0·9	1·1	1·3	,,	,,	,,
	10	1·1	1·4	1·8	2·2	2·5	,,	,,	,,
	15	1·6	2·2	2·7	3·2	3·8	,,	,,	,,
	20	2·2	2·9	3·6	4·3	5·0	,,	,,	,,
	25	2·7	3·6	4·5	5·4	6·3	,,	,,	,,
	30	3·2	4·3	5·4	6·5	7·6	,,	,,	,,
	35	3·8	5·0	6·3	7·6	8·8	,,	,,	,,
	40	4·3	5·8	7·2	8·6	10·1	,,	,,	,,
2¼ inches.	5	0·4	0·6	0·7	0·9	1·0	1·1	,,	,,
	10	0·9	1·1	1·4	1·7	2·0	2·3	,,	,,
	15	1·3	1·7	2·1	2·6	3·0	3·4	,,	,,
	20	1·7	2·3	2·8	3·4	4·0	4·5	,,	,,
	25	2·1	2·8	3·6	4·3	5·0	5·7	,,	,,
	30	2·6	3·4	4·3	5·1	6·0	6·8	,,	,,
	35	3·0	4·0	5·0	6·0	7·0	8·0	,,	,,
	40	3·4	4·5	5·7	6·8	8·0	9·1	,,	,,
2½ inches.	5	0·3	0·5	0·6	0·7	0·8	0·9	1·0	,,
	10	0·7	0·9	1·2	1·4	1·6	1·8	2·1	,,
	15	1·0	1·4	1·7	2·1	2·4	2·8	3·1	,,
	20	1·4	1·8	2·3	2·8	3·2	3·7	4.1	,,
	25	1·7	2·3	2·9	3·5	4·0	4·6	5·2	,,
	30	2·1	2·8	3·5	4·1	4·8	5·5	6·2	,,
	35	2·4	3·2	4·0	4·8	5·6	6·4	7·3	,,
	40	2·8	3·7	4·6	5·5	6·4	7·4	8·3	,,
	45	3·1	4·1	5·2	6·2	7·3	8·3	9·3	,,
	50	3·5	4·6	5·8	6·9	8·1	9·2	10·4	,,
2¾ inches.	5	0·3	0·4	0·5	0·6	0·7	0·8	0·9	1·0
	10	0·6	0·8	1·0	1·1	1·3	1·5	1·7	1·9
	15	0·9	1·1	1·4	1·7	2·0	2·3	2·6	2·9
	20	1·1	1·5	1·9	2·3	2·7	3·0	3·4	3·8
	25	1·4	1·9	2·4	2·9	3·3	3·8	4·3	4·8
	30	1·7	2·3	2·9	3·4	4·0	4·6	5·1	5·7
	35	2·0	2·7	3·3	4·0	4·7	5·3	6·0	6·7
	40	2·3	3·0	3·8	4·6	5·3	6·1	6·8	7·6
	45	2·6	3·4	4·3	5·1	6·0	6·8	7·7	8·6
	50	2·9	3·8	4·8	5·7	6·7	7·6	8·6	9·5
3 inches.	5	0·2	0·3	0·4	0·5	0·6	0·6	0·7	0·8
	10	0·5	0·6	0·8	1·0	1·1	1·3	1·4	1·6
	15	0·7	1·0	1·2	1·4	1·7	1·9	2·2	2·4
	20	1·0	1·3	1·6	1·9	2·2	2·6	2·9	3·2
	25	1·2	1·6	2·0	2·4	2·8	3·2	3·6	4·0
	30	1·4	1·9	2·4	2·9	3·4	3·8	4·3	4·8
	35	1·7	2·2	2·8	3·4	3·9	4·5	5·0	5·6
	40	1·9	2·6	3·2	3·8	4·5	5·1	5·8	6·4
	45	2·2	2·9	3·6	4·3	5·0	5·8	6·5	7·2
	50	2·4	3·2	4·0	4·8	5·6	6·4	7·2	8·0
	55	2·6	3·5	4·4	5·3	6·2	7·0	7·9	8·8
	60	2·9	3·8	4·8	5·8	6·7	7·7	8·6	9·6
3¼ inches.	5	0·2	0·3	0·3	0·4	0·5	0·5	0·6	0·7
	10	0·4	0·5	0·7	0·8	1·0	1·1	1·2	1·4
	15	0·6	0·8	1·0	1·2	1·4	1·6	1·8	2·0
	20	0·8	1·1	1·4	1·6	1·9	2·2	2·4	2·7
	25	1·0	1·4	1·7	2·1	2·4	2·7	3·1	3·4
	30	1·2	1·6	2·0	2·5	2·9	3·3	3·7	4·1
	35	1·4	1·9	2·4	2·9	3·3	3·8	4·3	4·8
	40	1·6	2·2	2·7	3·3	3·8	4·4	4·9	5·4
	45	1·8	2·4	3·1	3·7	4·3	4·9	5·5	6·1
	50	2·0	2·7	3·4	4·1	4·8	5·4	6·1	6·8
	55	2·2	3·0	3·7	4·5	5·2	6·0	6·7	7·5
	60	2·4	3·2	4·1	4·9	5·7	6·5	7·3	8·2

Diameter of the blast-pipe.	Velocity of the engine, in miles per hour.	Effective pressure against the piston, in lbs. per square inch, the vaporization of the boiler, in cubic feet of water per hour, being: 30	40	50	60	70	80	90	100
	miles.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.
3½ inches.	5	0·2	0·2	0·3	0·4	0·4	0·5	0·5	0·6
	10	0·4	0·5	0·6	0·7	0·8	0·9	1·1	1·2
	15	0·5	0·7	0·9	1·1	1·2	1·4	1·6	1·8
	20	0·7	0·9	1·2	1·4	1·6	1·9	2·1	2·3
	25	0·9	1·2	1·5	1·8	2·1	2·4	2·7	2·9
	30	1·1	1·4	1·7	2·1	2·5	2·8	3·2	3·5
	35	1·2	1·6	2·0	2·5	2·9	3·3	3·7	4·1
	40	1·4	1·9	2·3	2·8	3·3	3·8	4·2	4·7
	45	1·6	2·1	2·6	3·2	3·7	4·2	4·8	5·3
	50	1·8	2·4	2·9	3·5	4·1	4·7	5·3	5·9
	55	1·9	2·6	3·2	3·9	4·5	5·2	5·8	6·5
	60	2·1	2·8	3·5	4·2	4·9	5·6	6·4	7·0
3¾ inches.	5	0·2	0·2	0·3	0·3	0·4	0·4	0·5	0·5
	10	0·3	0·4	0·5	0·6	0·7	0·8	0·9	1·0
	15	0·5	0·6	0·8	0·9	1·1	1·2	1·4	1·5
	20	0·6	0·8	1·0	1·2	1·4	1·6	1·8	2·0
	25	0·8	1·0	1·3	1·5	1·8	2·1	2·3	2·6
	30	0·9	1·2	1·5	1·8	2·1	2·5	2·8	3·1
	35	1·1	1·4	1·8	2·1	2·5	2·9	3·2	3·6
	40	1·2	1·6	2·0	2·5	2·9	3·3	3·7	4·1
	45	1·4	1·8	2·3	2·8	3·2	3·7	4·1	4·6
	50	1·5	2·1	2·6	3·1	3·6	4·1	4·6	5·1
	55	1·7	2·3	2·8	3·4	3·9	4·5	5·1	5·6
	60	1·8	2·5	3·1	3·7	4·3	4·9	5·5	6·1
4 inches.	5	0·1	0·2	0·2	0·3	0·3	0·4	0·4	0·5
	10	0·3	0·4	0·5	0·5	0·6	0·7	0·8	0·9
	15	0·4	0·5	0·7	0·8	0·9	1·1	1·2	1·4
	20	0·5	0·7	0·9	1·1	1·3	1·4	1·6	1·8
	25	0·7	0·9	1·1	1·4	1·6	1·8	2·0	2·3
	30	0·8	1·1	1·4	1·6	1·9	2·2	2·4	2·7
	35	0·9	1·3	1·6	1·9	2·2	2·5	2·8	3·2
	40	1·1	1·4	1·8	2·2	2·5	2·9	3·2	3·6
	45	1·2	1·6	2·0	2·4	2·8	3·2	3·6	4·1
	50	1·4	1·8	2·3	2·7	3·2	3·6	4·1	4·5
	55	1·5	2·0	2·5	3·0	3·5	4·0	4·5	5·0
	60	1·6	2·2	2·7	3·2	3·8	4·3	4·9	5·4

CHAPTER VIII.

OF THE FRICTION OF LOCOMOTIVE ENGINES.

ARTICLE I.

OF THE FRICTION OF UNLOADED LOCOMOTIVE ENGINES.

Sect. I. *Of the divers elements of the friction of locomotive engines.*

After having examined the resistance offered by the loads to be moved, it will be proper also to make known the passive resistance or friction of the movers which we have to employ; for it is only the surplus of their power over and above what is necessary to propel themselves, that these movers can apply to the drawing of burdens.

While a locomotive engine is performing the traction of a train, it evidently requires:—1st, a certain force to make the train advance, or to overcome the resistance of all the loaded carriages; and 2dly, another force to propel itself by overcoming its own friction. It is this second force, that which causes the engine to move, which represents the

friction of the engine; whereas the first is *the resistance of the load,* and the union of the two efforts constitutes the *total force applied by the mover.*

The friction of a locomotive engine is then the force it expends to maintain itself in motion on the rails. But that force must clearly vary according to the weight or resistance of the load which the engine draws. In effect, the greater that weight, the greater also will be the pressure it causes on the axes of rotation, and on the divers moving parts of the apparatus; and as the friction is always in proportion to the pressure, it follows that the friction which takes place at these points, must augment with the load. Hence the friction of the engine, which is nothing more than the force resulting from the union of these different frictions, must equally increase with the load.

Thus, we shall first establish a difference between the friction of an engine *unloaded,* and that of the same engine *loaded.*

On the other hand, the force requisite to set in motion an *unloaded* engine may itself be decomposed into two portions arising from two distinct causes: 1st, that which is necessary to overcome the friction of all the parts of the apparatus itself, and which would be observed if the engine were supported on its axles and did not propel its own weight along the rails; and 2dly, that which is necessary to execute the progressive motion, that is, to overcome the

particular friction caused on the axles and wheels by the weight of the engine, as in other carriages.

Finally, then, we will consider the friction of a locomotive engine, under any circumstances whatever, as composed of the three following resistances:

1st. The resistance due to the friction of its mechanical organs.

2d. The resistance arising from the weight of the engine, considered as a carriage.

3d. The additional friction, caused in the engine, by the load it draws.

If we knew these three elements of the total resistance separately, it is plain that we could, under all circumstances, conclude from them the friction of a locomotive engine whose construction, weight and load, were known. These must then be the present object of our inquiry.

To attain our end, we shall first seek to determine the friction of *unloaded* engines, which is the sum of the two first of the resistances mentioned above; and deducting from this the resistance of the engine considered as a carriage, which may easily be done, since in this respect the engines may be assimilated to waggons, we shall obtain the friction of the mechanical organs of the engine. Thence we shall pass to the second part of our inquiry, which will consist in determining the *additional* friction of the engines, according to the load they draw.

SECT. II. *Of the different modes of determining the friction of unloaded engines.*

The force necessary to move an unloaded locomotive engine may differ according to two different circumstances:

1st. The steam remaining shut in the boiler, and having no access to the mechanism nor exerting any pressure on it, so that the progression of the engine be produced by an external agent.

2nd. The steam being the agent which produces the motion.

The difference between these two cases cannot be very great; for in both circumstances the load of the engine remains the same, being no other than its own weight. Besides, whatever be the means that make it move, it goes forward; thus at each turn of the wheel there is a complete revolution, and therefore a complete friction, of all the mechanism. The steam, in order to move the engine, would have applied a certain force. That force would have produced pressure, and consequently proportional friction, on all the points compressed. Now, the moment we make the engine advance, we apply a force equal to that which the steam would have applied. Thus we produce on all the joints the same pressure, and consequently the same friction, as the force of the steam would have produced. Of all these joints

or moving parts, it is only those, therefore, whereon the steam acts in a direct and particular manner, which are not equally compressed in both cases. These parts being strongly pressed one against the other when the steam is admitted into the cylinders, cease to experience that pressure, and in consequence have indisputably less friction, when the steam takes no part in creating the motion. But the parts on which the steam exerts a direct pressure are merely the two slides.

The surface of the slide, on which the pressure of the steam acts, is generally 7½ inches by 6, or 45 square inches; which makes 90 square inches for the two slides. When we suppose the engine moving alone, and without drawing any train after it, we cannot suppose that the effective pressure of the steam in the boiler need be more than 10 ℔s. per square inch. We shall see by experiment that it may be no more than 4 or 5 ℔s. The pressure made by the steam on the slides is then, at most, 900 ℔s. Taking the friction of iron against iron, polished and lubricated with oil, at $\frac{1}{10}$ of the pressure, it would be a friction of 90 ℔s. But it is well known that a force applied at one point of an engine, when transmitted to another point of the same engine, changes its intensity in the inverse ratio of the velocity of the points considered. The slide moves but 3 inches at each stroke of the piston, or ½ foot at each turn of the wheel, that is to say, it traverses but ½ a foot, while

the engine, having a wheel of 5 feet in diameter, advances 15·71 feet. The friction of the slide, therefore, considered as opposing the motion of the engine, creates at most a definitive resistance of but $\frac{90 \text{ lbs.}}{2 \times 15{\cdot}71}$, or about 3 lbs. Whence it is seen that in practice the friction determined, either in the first case, or in the second, may be considered as the true friction of the engine when it draws no load.

Sect. III. *Fricton of the engines determined by the smallest pressure of steam necessary to keep them in motion.*

The reflections developed above, and tending to prove that the force necessary to move an engine is sensibly the same, whether the power of the steam itself be employed to set it in motion, or any external agent be used, gave us three means of attaining the knowledge of the friction of the engines when drawing no load. The first consisted in seeking what was the least pressure of steam requisite for a locomotive to maintain itself in motion on the rails, when it had no more than its own friction to overcome; the second was the use of the dynamometer; and the third was the method of the angle of friction, already employed with respect to waggons. All three were tried successively.

The principle on which the first of these methods is founded is this: if the steam, exerting a known effective pressure per square inch, or per unit of surface of the piston, be found sufficient to keep the engine in motion, at a velocity however small, but yet at a uniform velocity, it follows that the effort then developed is just sufficient to hold the friction of the engine in equilibrio; for if it were greater, the velocity would increase, and were it less, the velocity would diminish. In this case, then, in order to obtain the measure of the friction, it suffices to calculate the effort applied by the engine, which is easy, since the area of the two pistons is known, as well as the pressure exerted by the steam per square inch of their surface.

It must only be observed, according to the principle already mentioned, that the pressure exerted on one part of an engine, on being transmitted to another part of the same engine, reduces itself in the inverse proportion of the velocity of the points of application. In the case before us, the velocity of the engine is to that of the piston, as the circumference of the wheel is to twice the stroke, since the piston makes two strokes while the wheel performs one turn. A force applied on the piston produces then, for the progression of the engine, only a force reduced in the inverse proportion of these velocities, that is to say, as twice the stroke is to the circumference of the wheel.

Let d be the diameter of the piston, $\frac{1}{4}\pi d^2$ will be the area of one of the two pistons; $P-p$ being the *effective* pressure of the steam per unit of surface,

$$\frac{1}{2}\pi d^2 \, (P-p)$$

will be the effective pressure on both pistons. If, moreover, l express the length of the stroke of the piston, and D the diameter of the wheel, the effective force of translation resulting for the engine, in virtue of this pressure, will be then

$$\frac{1}{2}\pi d^2 \, (P-p) \times \frac{2l}{\pi D} \quad \text{or} \quad \frac{(P-p)\, ld^2}{D},$$

which, from what has been said, will give the measure of the friction of the engine.

It must be noted, that the pressure of the steam in the cylinder is here taken as equal to that which exists in the boiler. The reason of it is that, in the experiments which we shall have to make by that mode, the motion of the engines being always extremely slow and the regulator entirely open, the two pressures will have time to settle in equilibrio, and therefore will be equal to each other.

To ascertain the smallest pressure capable of moving the engine, it was necessary to take that engine at a time when it was producing steam at a very low degree of elasticity. The evening, after the work was done, and the fire thrown out of the fire-box, when the water in the boiler was beginning to lose its heat, and the steam arising from it was

gradually losing its force, was the moment favourable for trying the smallest pressure at which the engines could move along the rails. The spring-balance, which closed the safety-valve, showed the pressure of the steam in the boiler, by loosening the spring till it was precisely in equilibrio with that pressure; and to make the observation more sure, the engine was immediately brought to the stationary syphon-manometer, and that instrument gave the true pressure per square inch in the boiler at the moment of the experiment. In this manner were made the following experiments, of which we shall only give the first in detail.

On the 5th July, 1834, the engine Atlas, cylinder 12 inches, stroke of the piston 16 inches, weight 11·40 tons, wheels 5 feet, 4 wheels coupled, was submitted to the experiment separate from its tender.

The spring of the balance being loosened more and more, to show the pressure of the steam in the boiler, as it gradually lowered, the following trials were made.

At 2 ℔s. of pressure marked on the balance, the engine moved forwards and backwards, passing from rest to motion, or surmounting, besides the friction, what is called the *vis inertiæ* of the mass of the engine; that is to say, not only preserving an acquired velocity, but acquiring it; which proves an excess in the moving power above the resistance.

At 1 ℔. of pressure similarly marked, the engine

started, passing again from the state of rest to that of motion.

The pressure still lowering a little, and the balance being at zero, the engine *continued* to move. At this moment it was brought under the manometer. The instrument marked 4 lbs. of effective pressure per square inch in the boiler, the valve then bearing merely the weight of the lever or something less, which was not discernible on the balance, as the lowest pressure it could indicate was that of the lever.

The cylinder being 12 inches in diameter, the area of the two pistons was 226 square inches. Thus a pressure of 4 lbs. per square inch produced on the piston a force of $226 \times 4 = 904$ lbs., that is to say, it could move a resistance of 904 lbs. at the velocity of the piston. But at the velocity of the engine, which is greater in the proportion of the circumference of the wheel to twice the stroke, or in the ratio of $\frac{15 \cdot 71}{2 \times 1 \cdot 33} = 5 \cdot 887$, that same force could overcome only a resistance of $\frac{904 \text{ lbs.}}{5 \cdot 887} = 154$ lbs.

Thus, as we have seen that the engine still moved at the moment when it was put under the manometer, though the pressure was then reduced to 4 lbs., it is plain that the resistance of the engine did not exceed 154 lbs.

This first experiment had been made with the

engine separate from its tender, with a view not to entangle one resistance with another; but wishing to apply it to lighter engines with uncoupled wheels, an inconvenience occurred. The pressure necessary to move the engine alone without tender was so low that the spring-balance could not indicate it, that pressure being less than the weight of the lever itself. Another inconvenience of this low pressure was, that it could not be obtained till the moment when the boiler produced no steam at all; so that the pressure was then lowering so rapidly that the accuracy of the experiment could not be depended on.

But as the resistance of the tender-carriage might easily be calculated from the experiments made on the friction of the carriages already inserted above, it was easy to take account of it. Thus the tender being left attached to the engine, the experiments offered the same degree of accuracy, with greater facility in observing the pressure of the steam. For this reason, in the following experiments the tender-carriage was no longer separated from the engine.

These experiments were made in a manner entirely similar to the one we have just explained; save, that to deduce from them the friction proper to the engine itself, we subtracted for the traction of the tender, first 6 lbs. per ton, and again 1 lb. per ton for the *additional* friction which every ton of that load produced in the engine, according to what will

be seen in the second article of this chapter. We shall only, therefore, present in the following Table the elements and the results of these experiments. We have neglected the resistance due to the blast-pipe, on account of the slowness of the motion, and especially of the little vaporization which took place in the boiler.

Experiments on the friction of locomotive engines, by the least pressure of steam necessary to keep them in motion.

Number of the experiment.	Date of the experiment.	Name of the engine.	Diameter of the cylinder.	Stroke of the piston.	Diameter of the wheel.	Weight of the engine.	Weight of the tender attached to the engine.	Effective pressure per sq. inch, necessary to maintain the motion.	Friction of the engine.	Observations.
			inches.	inches.	feet.	tons.	tons.	lbs. per sq. in.	lbs.	
I.	July 5, 1834.	ATLAS.	12	16	5	11·40	,,	4·00	154	engine with 4 coupled wheels.
II.	July 21, 1834.	SUN.	11	16	5	7·91	6·50	5·50	132	engine with 4 wheels not coupled.
III.	July 23, 1834.	SUN.	11	16	5	7·91	6·50	4·75	108	engine with 4 wheels not coupled.
IV.	July 23, 1834.	FIREFLY	11	18	5	8·74	6·50	4·50	118	engine with 4 wheels not coupled.
V.	Aug. 3, 1836.	STAR.	14	12	5	11·20	5·50	5·50	177	engine with 6 wheels not coupled.

SECT. IV. *Friction of the engines, determined by the dynamometer.*

At the same time that the friction of the engines was determined in this manner, other essays were also made to obtain the valuation of that friction by means of the dynamometer.

On the 22nd of July, the engine VULCAN, cylinder 11 inches, stroke 16 inches, wheels 5 feet, weight 8·34 tons, one pair of wheels only worked by the piston, being ready to start for Manchester, its boiler full of water, and fire-box full of coke, was separated from its tender. A circular spring-balance was fixed to the engine, and a lever passed through the ring of the balance, for two men to draw the engine by means of the lever.

The engine was first set in motion by five or six men. As soon as the first impulse was given, the two men at the lever kept it in motion without difficulty at the velocity of between 2 and 3 miles per hour. The style of the balance oscillated considerably; it went generally from 130 lbs. to 170 lbs., giving a mean traction of 150 lbs.

The balance was then taken off the front of the engine and fixed on the hinder part, then turned towards Liverpool, and the same experiment renewed gave a mean traction of 140 lbs. The style still oscillated, in general, some twenty pounds above and below that point.

Mean of these two experiments 145 lbs.

The engine was ready to start, and had already taken a few runs on the rails to get up the fire and fill the boiler. Thus the greases which served to lubricate the rubbing parts were melted, and the oils quite liquid. But the experiments being made within the enclosure of the station, on a place of continual thoroughfare, where the rails are constantly covered with cinders and dirt, this circumstance must have greatly augmented the resistance to the motion.

We here subjoin the Table of three other experiments, made in a similar manner.

Experiments on the friction of unloaded locomotive engines, by the dynamometer.

Number of the experiment.	Date of the experiment.	Name of the engine.	Diameter of the cylinder.	Stroke of the piston.	Diameter of the wheel.	Weight of the engine.	Friction of the engine.
			inches.	inches.	feet.	tons.	lbs.
VI.	July 22, 1834.	VULCAN.	11	16	5	8·34	145
VII.	July 23, 1834.	SUN.	11	16	5	7·91	115
VIII.	Do.	FIREFLY.	11	18	5	8·74	127
IX.	Do.	FURY.	11	16	5	8·20	105

SECT. V. *Friction of the engines, determined by the angle of friction.*

The results obtained by the dynamometer were not very far different from those obtained by the least pressure; but as in all these experiments, the

style of the balance oscillated exceedingly, in consequence of the little inequalities of the way, or the jerks given by the men who drew the engine, it was very difficult to ascertain the mean traction. It was very desirable, therefore, to determine the friction of the engines by a different method, in which that cause of error should not exist.

For this reason the engines were submitted to the same experiments that had served to determine the friction of the waggons.

These experiments having been made and calculated exactly like those on the waggons, we shall merely give their results in the following Table. Account was taken of the resistance of the air against the wheels, in the same manner as in the experiments on the friction of waggons.

Experiments on the friction of unloaded locomotive engines, by the angle of friction.

Number of the experiment.	Date of the experiment.	Name of the engine.	Weight of the engine.	Effective surface presented to the resistance of the air.	Height of fall on the first plane.	Distance traversed on the first plane.	Height of fall on the second plane.	Distance traversed on the second plane.	Friction of the engine.	Observations.
			tons.	sq. feet.	feet.	feet.	feet.	feet.	lbs.	
X.	July 30, 1834.	Jupiter.	7·90	42	34·61	3300	2·17	2889	79	
XI.	July 31, 1834.	Atlas.	11·40	48	30·06	2871	2·01	2583	123	
XII.	Aug. 1, 1834.	Atlas.	11·40	48	34·61	3300	0·79	1365	173	The connecting rods of the wheels too tight.
XIII.	Aug. 1, 1834.	Vesta.	8·71	42	34·61	3300	0·46	363	181	The engine, fresh from the workshop, where it has been repaired, is still rather stiff.
XIV.	Aug. 2, 1834.	Fury.	8·20	42	34·61	3300	2·07	2698	87	
XV.	Aug. 2, 1834.	Vulcan.	8·34	42	34·89	3327	1·63	2064	104	
XVI.	Aug. 4, 1834.	Leeds.	7·07	42	34·61	3300	1·71	2172	82	
XVII.	Aug. 15, 1834.	Leeds.	7·07	42	34·61	3300	1·25	1761	87	
XVIII.	Aug. 8, 1836.	Star.	11·20	48	34·61	3300	1·09	1635	175	

SECT. VI. *Table of the results of the preceding experiments on the friction of unloaded engines.*

Finally, for the convenience of making researches, we unite the results of these different experiments in one Table.

Synopsis of the preceding experiments, on the friction of unloaded locomotive engines.

Number of the experiment.	Name of the engine.	Diameter of the cylinder.	Stroke of the piston.	Diameter of the wheel.	Weight of the engine.	Mode of determination.	Friction resulting from the experiment.	Friction of the engine.	Observations.
		inches.	inches.	feet.	tons.		lbs.	lbs.	
II.	SUN.	11	16	5	7·91	by the least pressure	132	118	Engine with 4 wheels not coupled.
III.	—	—	—	—	—	by the least pressure	108		
VII.	—	—	—	—	—	by the dynamometer	115		
IV.	FIREFLY.	11	18	5	8·74	by the least pressure	118	123	do.
VIII.	—	—	—	—	—	by the dynamometer	127		
VI.	VULCAN.	11	16	5	8·34	by the dynamometer	145	125	do.
XV.	—	—	—	—	—	by the angle of friction	104		
IX.	FURY.	11	16	5	8·20	by the dynamometer	105	96	do.
XIV.	—	—	—	—	—	by the angle of friction	87		
XVI.	LEEDS.	11	16	5	7·07	by the angle of friction	82	85	do.
XVII.	—	—	—	—	—	by the angle of friction	87		
X.	JUPITER.	11	16	5	7·90	by the angle of friction	79	79	do.
XIII.	VESTA.	11½	16	5	8·71	by the angle of friction	181	181	Do. The engine, just come from the workshop, where it has been repaired, is rather stiff.
I.	ATLAS.	12	16	5	11·40	by the least pressure	154	139	Engine with 4 wheels coupled.
XI.	—	—	—	—	—	by the angle of friction	123		
XII.	—	—	—	—	—	by the angle of friction	173	173	The connecting rods of the wheels too tight.
V.	STAR.	14	12	5	11·20	by the least pressure	177	176	Engine with 6 wheels not coupled.
XVIII.	—	—	—	—	—	by the angle of friction	175		

In all these experiments we find that those made on the inclined plane give less friction than those made in the enclosure of the station, whether by the dynamometer or by the least pressure. This result has already been explained by the sand, cinders, or mud, which always cover the rails at the station; but, on the other hand, in the experiments made on the inclined planes, if the regulator of the engine did not close the passage hermetically, a slight escape of steam may have taken place in the cylinders, and in a certain degree favoured the motion of the engine. The results then of the two modes of experiment deviate contrary ways, and the difference between them not being very considerable, we have reason to think that their mean gives the result required with an accuracy sufficient for practice.

Examining these experiments, to deduce from them a general datum, and leaving out the engine Vesta, which was found to be in an exceptional case, we perceive that engines such as the Sun, Firefly, Vulcan, Fury, Leeds, and Jupiter, of an average weight of 8 tons, and with four wheels not coupled, have a mean friction of 104 ℔s.

That the engine Atlas, of the weight of 11 tons, having six wheels, four only of which are conical and with flanges, but coupled, has a friction of 139 ℔s.

And finally, that the engine Star, of the weight

of 11 tons, with six flanged wheels, has a friction of 176 lbs.

We shall presently see that these differences depend in part on the weight of the engines. But it will readily be conceived that the friction being influenced by so many different circumstances, it is impossible to imagine that it can be identically the same, not merely in engines of a different construction, but even in engines perfectly similar to each other, and coming from the very same builders. The observed differences ought not then to surprise.

Sect. VII. *Of the friction of the mechanical organs of the engine, and of its friction as a carriage.*

In the preceding paragraphs we have determined the friction of unloaded engines; but we have already said that this friction is composed of two parts, viz., the resistance arising from the weight itself of the engine, considered as a heavy carriage to be drawn along the rails; and that which results from the friction of the different parts of the mechanism, and which would equally take place if the progressive motion did not exist. As the first of these two forces varies with the weight of the engine, and as the second, on the contrary, is nearly constant for engines of the same proportions, it will be proper now to estimate them severally in the total friction of the unloaded engine.

We have seen above that locomotives such as SUN, FIREFLY, VULCAN, FURY, LEEDS, and JUPITER, have a mean friction of 104 lbs. In the state in which those engines were submitted to experiment, their load was their own weight. Now we know that a weight of 1 ton, carried on waggons with springs as we have described, opposes to the traction on a railway a resistance of 6 lbs., and we shall presently see that the effort of this traction creates, moreover, in the engine, an additional friction of $\cdot 162 \times 6$ lbs. $= \cdot 97$ lb.; which makes in all 7 lbs. per ton. On the other hand, the engines, considered as carriages, are of a construction quite similar to that of the waggons. The wheels and axle-trees have not indeed the same dimensions in both cases. In the engines, the axle-bearings are somewhat thicker in proportion to the diameter of the wheels, which is disadvantageous as to the friction on the axle, but the difference is trifling; and again, the wheels of the engines being larger, offer somewhat less resistance as to the friction of rolling. Besides, they are greased, and kept with more care. We may therefore, without any important error, assimilate the engines to waggons with reference to their friction as carriages. Then it will be easy to deduce from the total friction of the engine the portion attributable to its weight, and the remainder will be the friction of the machinery. The engines which have just occupied our attention, and whose friction is 104 lbs., are of

the average weight of 8 tons; they create then, as carriages, a total resistance of 56 lbs., and consequently the friction of their mechanical organs amounts to 48 lbs.

As to the ATLAS engine, the passive resistance of which is 139 lbs., the same calculation makes the friction of the mechanical organs amount to 59 lbs.; and there is room to think that the excess of this number above the preceding depends on the coupling of the wheels of the engine.

With respect to the engine STAR, we can draw no conclusion, for want of knowing precisely the friction of a carriage borne on six *flanged* wheels, as that engine is.

These calculations authorise us then to consider the resistance of the mechanical organs in engines of the kind described above, and when in good order, as being at a medium from 48 to 59 lbs.

Consequently, to value in pounds the friction of an unloaded locomotive engine, the number 48, or the number 59, which, according as the engine has its wheels unconnected or coupled, represents the friction of its mechanical organs, must be added to its total friction as a carriage, which is no other than the product of its weight expressed in tons by the number 7.

The same result will be attained approximatively by simply taking the friction of the engines at 15 lbs. per ton of their weight, that is, at twice and a half the friction of the waggons.

This manner of estimating the friction of the engines is useful whenever it is wished to calculate the effect that may be expected from them, without having recourse to an immediate experiment. But it is especially necessary, when, before constructing a locomotive, it is required to determine the proportions it ought to have in order to produce desired effects. In this case, indeed, the calculation cannot be performed without employing in it the presumed friction of the engine, and as the weight intended for the engine is always decided previously, it will be easy to derive the friction it will have, if it be properly constructed.

ARTICLE II.

OF THE ADDITIONAL FRICTION OF LOADED LOCOMOTIVE ENGINES.

SECT. I. *Of the mode of determination.*

We have just determined the friction of locomotive engines when they draw no load but their own weight. But those engines are never employed in that way, and we have shown that the friction of the same engine must become greater as it draws a greater weight; because the augmentation of weight increases the pressure exerted on the different moving parts of the apparatus, and with the pressure increases necessarily also the corresponding friction. We shall now, therefore, endeavour to

determine the precise value of this surplus of resistance produced in the engine by virtue of the load which it draws.

When an engine performs the traction of a train, the pressure of the steam in the boiler is known from inspection of the manometer or of the balance of the safety-valve. But the pressure of that steam in the cylinder is not known, because in passing from the boiler to the cylinder it alters its elastic force, as will be seen further on. If the pressure in the cylinder could be known *à priori*,—if, for instance, it were possible to apply a manometer to the cylinder, then would immediately be deduced what is the friction of the engine corresponding to that load.

In effect, since by hypothesis the pressure in the cylinder or on the piston would be known, calculating the total effect of that pressure on the area of the piston, we should have the exact valuation of the power applied by the engine. Now, from other sources is known also the resistance opposed to the motion, for it consists of the gravity, the friction of the train, the resistance of the air, the resistance caused by the blast-pipe, and the friction of the engine.

Besides, if the engine, in drawing this load, were constantly to increase its velocity, there would plainly be excess of the power over the resistance; if, on the contrary, the velocity were gradually to lessen, the power would be inferior to the resist-

ance; but if the engine be observed at a moment when it has acquired a certain uniform velocity, and that velocity be maintained without alteration, the effort then applied by the engine must necessarily be precisely equal to the resistance which is opposed to it; for, were it not so, there would be acceleration or retardation of motion.

Thus, the effort applied by the engine and the resistance opposed to the motion would be known, and by making these two quantities equal to each other, we should thence deduce the friction proper to the engine.

This mode then would give immediately the friction of the engine, if the pressure in the cylinders were known.

But there are cases wherein the pressure in the cylinder is in effect known *à priori*, and is no other than the pressure in the boiler itself. These cases are those wherein the engine attains the limit of its power with the pressure at which it works, that is to say, when it draws the greatest load it can draw with that pressure.

In effect, since by hypothesis the engine has attained the limit of its power, the pressure in the cylinder cannot be less than in the boiler; for if it were, by diminishing the velocity, which is the only obstacle to the equilibrium of pressure being established between the two vessels, we might give the steam time to rise in the cylinder to a pressure equal to that of the boiler, and then the effect would be

augmented. That is to say, the engine would draw a greater load, which is against the hypothesis. On the contrary, as soon as the pressure in the cylinder is become equal to that of the boiler, no subsequent diminution of velocity will admit of increasing the load; for that increase of load requires an increase of intensity in the motive force, that is, in the pressure of the steam on the piston, which is no longer possible.

Thus, in the case wherein the maximum load of the engine is attained, we know *à priori* the effort applied, and can, as has been explained above, deduce from thence the corresponding friction of the engine.

Suppose then, in an experiment, this limit of the power of the engine to be attained. Let d be the diameter of the piston, and π the ratio of the circumference to the diameter, $\frac{1}{4}\pi d^2$ will be the area of one piston, and $\frac{1}{2}\pi d^2$ the area of the two pistons together. Again, let $(P-p)$ be the effective pressure of the steam, per unit of surface, during the experiment; it is clear, from what has been said above, that $\frac{1}{2}\pi d^2\ (P-p)$ will be the force which was then applied on the piston.

Calling D the diameter of the wheel, and l the length of the stroke, that force applied on the piston was, on transmitting itself to the engine, reduced in the inverse ratio of the respective velocities, or in the ratio $\frac{2l}{\pi D}$. Thus, after transmission to the engine, it had for its expression:

$$\tfrac{1}{2}\pi d^2 (\mathrm{P}-p) \frac{2l}{\mathrm{D}} = (\mathrm{P}-p) \frac{d^2 l}{\mathrm{D}}.$$

This is then the expression of the force of traction applied to the progression of the engine.

Again, expressing by $p'v$ the effective pressure produced on the opposite face of the piston by the action of the blast-pipe, the resistance thence resulting against the progression of the engine was

$$p'v \frac{d^2 l}{\mathrm{D}}.$$

Similarly, M being the weight of the load, and m that of the engine, both expressed in tons, g the gravity, in pounds, of a ton placed on the inclined plane of the experiment, and, in fine, k expressing the friction of the carriages per ton,

$$(k+g)\,\mathrm{M} + gm$$

was the resistance opposed by the friction and the gravity, in ascending the inclined plane. Finally, if uv^2 represent the resistance of the air, at the velocity of the motion, and X the unknown friction of the loaded engine, we see that

$$(k+g)\,\mathrm{M} + gm + uv^2 + p'v\frac{d^2 l}{\mathrm{D}} + \mathrm{X}$$

was the total resistance opposed to the motion of the engine.

As we have seen that, by reason of the uniformity of the motion, the power was equal to the resistance, it follows that we had

$$(P-p)\frac{d^2l}{D}=(k+g)M+gm+uv^2+p'v\frac{d^2l}{D}+X,$$

and consequently, in fine,

$$X=(P-p-p'v)\frac{d^2l}{D}-(k+g)M-gm-uv^2.$$

This equation therefore gives the friction of the loaded engine.

To apply this expression to the numerical determination of the friction, attention must be paid to the manner of expressing the different quantities contained in it. P represents the total pressure of the steam in the boiler, p the atmospheric pressure, and $p'v$ the effective pressure owing to the blast-pipe; and these forces act against the surface of the piston. Thus, according as they are expressed in pounds per square inch, or in pounds per square foot, the diameter d of the piston must be measured in inches or in feet. The length l of the stroke, and the diameter D of the wheel, must be expressed either both in feet or both in inches, which is indifferent, since the equation contains only their ratio. The quantities k, g and uv^2 must, as we have said, be expressed in pounds, and in fine the definitive value of X will equally be expressed in pounds.

Sect. II. *Experiments on the additional friction of locomotive engines.*

The formula which we have just obtained is very simple, and gives easily the friction of the engine in all cases when it has attained the limit of its

power. All that remains to do, then, is to attain that point. In consequence, we undertook a series of experiments, sometimes taking the loads as great as the engine could draw, at other times limiting ourselves to a moderate load, but lowering the pressure in the boiler by means of the safety-valve, as much as possible without stopping the train.

The experiments in question were made on three inclined planes of the Liverpool and Manchester Railway, viz.: on the inclined plane of *Sutton*, inclined $\frac{1}{89}$, on that of *Whiston*, inclined $\frac{1}{96}$, and on the acclivity of *Chatmoss*, rising $\frac{1}{1300}$. In estimating the resistance on these planes, we took account of the gravity, as has been indicated in Chapter VI. As to the resistance of the air and that of the blast-pipe, we used the practical Tables which we have given on the subject. For that purpose, we note, in each experiment, the elements proper for the use of the Tables, viz.: the velocity of the engine, the mean vaporization of the boiler, the area of the blast-pipe, and the nature of the train in motion. With these data, there is no difficulty in finding, without calculation, the quantities which we have expressed above by uv^2 and $p'v$; and substituting them, with the dimensions of the engine and the other data of the problem, in the formula developed above, we thence conclude the additional friction of the engine.

The results thus obtained in the different experiments now before us, are collected in a Table which

we shall presently offer: to show however the proceeding which we have followed, and to make the nature of it better understood, we will here detail the calculation of the first of those experiments.

On the 22d July, 1834, the engine VULCAN, cylinder 11 inches, stroke of the piston 16 inches, wheel 5 feet, weight 8·34 tons, effective pressure in the boiler then 57·5 lbs. per square inch, ascended the inclined plane of *Sutton* with a train of 6 first-class coaches, the mail, and two empty trucks; weight of the train, tender included, 39·07 tons. The velocity of 26·6 miles per hour, before reaching the foot of the inclined plane, sunk to 7·5 miles per hour at the top of the plane.

With these data, we have to calculate successively the effort applied by the engine, and the resistance which was opposed to it. Now, the effective pressure observed in the boiler, was 57·5 lbs. per square inch. Moreover, in this engine the diameter of the blast-pipe was 2·25 inches, and the mean vaporization 60 cubic feet of water per hour. Consequently, from the Table given above, the resistance against the piston, caused by the blast-pipe, at the velocity of 7·5 miles per hour, was 1·3 lb. per square inch. The real disposable force of the engine then was $57·5 - 1·3 = 56·2$ lbs. This is the quantity which we have represented above by $(P - p - p'v)$.

This premised, the effort exerted by the engine might be calculated thus:

190 . . .	Area of the two pistons, in square inches, multiplied by
56·2 lbs.	Real effective pressure of the steam per square inch on the piston, gives
10678 lbs.	Force applied on the piston; which, transmitted as force of traction to the engine, whose velocity is 5·9 times as great, gives
$\frac{10678}{5 \cdot 9} = 1810$ lbs.	Definitive effort applied by the engine.

On the other hand, the resistance was:

$39 \cdot 07 \times 6 = 234$ lbs.	Resistance owing to the friction of the carriages.
$\frac{47 \cdot 41 \times 2240}{89} = 1193$ lbs.	Resistance caused by the gravity of the total mass, train and engine, on the plane inclined $\frac{1}{89}$;
25 lbs.	Resistance of the air against an effective surface of 170 square feet, at the velocity of 7·5 miles per hour.
1452 lbs.	Total resistance of the train.

Consequently, subtracting first the resistance of the train from the effort exerted by the engine, we have

$$\begin{array}{r} 1810 \\ -1452 \\ \hline 358 \end{array} \text{ lbs.,}$$

which is the total friction of the engine, corresponding to the above load. Moreover, if we again subtract 125 lbs. for the friction of the unloaded engine, there remains

$$\begin{array}{r} 358 \\ -125 \\ \hline 233 \end{array} \text{ lbs.;}$$

and this number consequently indicates the *additional* friction created in the engine by the resistance of 1452 lbs. Finally, then, the additional friction created by each pound of resistance or of traction imposed on the engine, is

$$\frac{233}{1452} = \cdot 161 \text{ lb.}$$

The other calculations are performed in a manner entirely similar. For this reason we content ourselves with presenting the data and the results of them in the following Table.

We have made a distinction between the engines with uncoupled wheels, and those with coupled wheels, because it is evident that in the latter, whose wheels are held together by connecting rods, the motion is communicated by a greater number of joints, and consequently all that tends to produce an additional friction must produce a more considerable one in them than in the engines with unconnected wheels.

Experiments on the additional friction of loaded locomotive engines.

Number of the experiment.	Date of the experiment.	Nature of the load, and weight of the train, tender included.	Inclination of the road.	Name of the engine.	Diameter of the cylinder.	Stroke of the piston.	Diameter of the wheel.	Weight of the engine.	Diameter of the blast-pipe.	Mean vaporization per hour.	Effective pressure in the boiler.	Minimum velocity of the experiment.	Friction of the engine without load.	Additional friction per lb. of resistance.	Observations.
		tons.			inches.	inches.	feet.	tons.	inches.	cub. ft.	lbs. per sq. in.	miles per hour.	lbs.	lbs.	
I.	July 22, 1834.	9 coaches 39·07	$\frac{1}{89}$	Vulcan	11	16	5	8·34	2·25	60·60	57·5	7·5	125	·161	
II.	July 22, 1834.	9 coaches 41·32	$\frac{1}{98}$	—	—	—	—	—	—	—	57·5	12·0	—	·126	
III.	July 24, 1834.	10 waggons 56·16	$\frac{1}{98}$	Fury.	11	16	5	8·20	2·25	54·45	65·5	3·33	96	·081	
IV.	Aug. 4, 1834.	8 coaches 37·97	$\frac{1}{89}$	—	—	—	—	—	—	—	55	10·0	—	·131	
V.	Aug. 15, 1834.	7 waggons 35·15	$\frac{1}{89}$	Leeds.	11	16	5	7·07	2·16	68·82	48·5	6·6	85	·120	
VI.	Aug. 9, 1836.	3 loaded waggons and 11 empty 38·58	$\frac{1}{89}$	Star.	14	12	5	11·19	2·0	68·79	50·5	8·57	176	·106	
VII.	Aug. 9, 1836.	21 empty waggons 41·97	$\frac{1}{89}$	—	—	—	—	—	—	—	51·2	6·26	—	·089	
VIII.	Aug. 16, 1834.	7 waggons 39·93	$\frac{1}{89}$	Vesta.	$11\frac{1}{8}$	16	5	8·71	2·50	65·00	57·25	2·50	181	·157	Engine fresh from repairing shop.
IX.	Aug. 16, 1834.	8 waggons 37·45	$\frac{1}{89}$	—	—	—	—	—	—	—	58	3·25	—	·234	
X.	Aug. 16, 1834.	8 waggons 39·05	$\frac{1}{89}$	—	—	—	—	—	—	—	56·5	3·0	—	·160	
		Mean for engines with uncoupled wheels												·137	
XI.	July 23, 1834.	40 waggons 195·50	$\frac{1}{1800}$	Atlas.	12	16	5	11·40	2·94	43·81	55	5·75	139	·231	
XII.	July 23, 1834.	8 waggons 39·40	$\frac{1}{89}$	—	—	—	—	—	—	—	55	6·0	—	·272	
XIII.	July 31, 1834.	8 waggons 40·15	$\frac{1}{89}$	—	—	—	—	—	—	48·21	51	7·5	—	·143	
		Mean for engines with coupled wheels												·215	

From these experiments, we perceive that in engines with uncoupled wheels, the additional friction created per ℔. of traction is ·137 ℔., that is to say, the friction is about $\frac{1}{7}$ of the resistance imposed on the engine; and that in engines with coupled wheels it amounts to ·215 ℔., or may be taken at half as much more than the preceding. It will readily be conceived, however, that it must vary with the construction and state of every engine. This is observable particularly in the engine Vesta, which, at the moment of the experiments, was not in a state of repair altogether satisfactory.

With reference to the manner in which the additional friction of engines ought to be calculated, we have to recall to mind that it is to be reckoned on every pound of the *total* resistance exerted against the motion; that is to say, the resistance caused by the friction of the waggons, that of gravity, and that of the atmospheric air, must first be calculated, and on the sum of these the additional friction of the engine is to be taken at the rate already indicated. It was in fact only by first introducing these different resistances into the account, that we have attained the above result; and consequently there can be no misunderstanding as to the manner in which the calculation should be done.

With respect to the resistance created directly on the piston, either by the atmospheric pressure or by the pressure arising from the blast-pipe, as these forces are destroyed by the opposed pressure of the

steam immediately, without the interposition of any action on the part of the mechanical organs of the engine, it is evident that they can create no additional friction in the engine. They ought not therefore to enter into this account.

Sect. III. *New developements on the mode of determination employed.*

An increase of friction in proportion to the load is founded on principle, as we have proved, and the mode of calculation which we have used will give exactly the measure of it, provided the engine be really arrived at the limit of its power with a given pressure, that is to say, at the *maximum* load that it can draw at that pressure. For the cases in which the engine slackened its velocity to the rate of 2 or 3 miles per hour, that point was evidently attained, since the engine was literally on the point of stopping. But moreover, it will presently be seen that for all cases in which the uniform velocity did not exceed 10 or 12 miles per hour, we were equally justified in taking the pressure on the piston as equal to that in the boiler.

In effect, the steam being at a certain degree of pressure in the boiler, passes into the steam-pipe, and from thence into the cylinder, where it at first expands, and would promptly rise to the same degree of pressure as in the boiler, if the piston were immoveable. This piston, however, offering on the

contrary but a certain resistance determined by the load which the engine draws, 40 lbs. per square inch for instance, will recede as soon as the elastic force of the steam in the cylinder shall have attained that point. A piston which withstands a resistance of but 40 lbs. per square inch, is nothing more than a valve loaded with 40 lbs. per square inch. If the communication between the boiler and the cylinder were completely open and without tube or contraction, the piston would become in reality a valve to the boiler; and that valve yielding before the safety-valve which is loaded, for instance, with 50 lbs. per square inch, the steam in the boiler could not rise above 40 lbs. As, however, the passage is contracted, the piston is not a valve to the boiler; but it still remains one for the cylinder.

From these three points it results: 1st, that the pressure in the cylinder is strictly equal to the resistance on the piston; 2ndly, that it is because the piston gives way and recedes before the steam, that the latter cannot augment its pressure beyond that point, and rise to the pressure of the boiler; but if by any means whatever the piston were rendered immoveable, or only that it did not give way faster than the steam is generated at the pressure of the boiler, an equilibrium of pressure would at once be established between the cylinder and the boiler; and 3rdly, that if there be in the steam-pipe a velocity greater than that which corresponds to the velocity

of generation of steam in the boiler, it is because the pressure is less in the cylinder than in the boiler, and that the fluid consequently seeks to settle in equilibrio in the two vessels. These observations show that the effective pressure on the piston may be calculated by that which exists in the boiler, as soon as the velocity of the piston is reduced to that of the generation of the steam. As we shall soon know by experiment, what is the total mass of steam, at the pressure of the boiler, produced by the engine in a given time, it will be easy to calculate how many cylinders full of steam, at that same pressure, the engine can supply in a minute, and thus what is the velocity which corresponds to what we call *full pressure in the cylinder*. We shall then see that for the engines under consideration, it is from 10 to 12 miles per hour, or thereabout. We may then consider that, in all the cases of uniform motion, wherein the velocity did not exceed that rate, the pressure in the cylinder was the same as that in the boiler; and therefore, in so calculating it, we had the exact measure of the power then applied by the engine.

CHAPTER IX.

OF THE TOTAL RESISTANCE ON THE PISTON, RESULTING FROM THE DIVERS PARTIAL RESISTANCES PRECEDENTLY MEASURED.

We have just estimated successively, in the preceding chapters, the divers resistances which oppose the motion of the engine. It is necessary now to seek the definitive resistance which results from them united, per square inch or per unit of surface of the area of the piston.

The resistances which we have hitherto considered are: the resistance of the air, the friction of the waggons, the gravity, the friction of the engines, and the resistance arising from the blast-pipe. But we must here add, besides, the atmospheric pressure; for the engines under consideration being high-pressure engines, it follows that the opposite face of the piston necessarily supports, like every other body in communication with the atmosphere, a certain pressure due to the elasticity of the atmospheric air.

In the calculations which we have hitherto made, we were enabled to suppress that force in the resistance, because at the same time we equally sup-

pressed it in the power, by calculating the latter only according to the *effective* pressure of the steam, that is to say, according to its surplus over the atmospheric pressure. This mode of proceeding was correct then, because, having to consider the power and the resistance only in the case of equality or equilibrium, and unmixed with any other consideration, we could without error retrench on both sides the same quantity. But as, in other questions which are about to present themselves, we shall want to consider the steam with reference to its volume, and as that volume depends on the *total* pressure at which the steam is generated, we must retain that *total* pressure, to express the elastic force of the steam; and consequently, must also let the atmospheric pressure remain in the resistance opposed to the motion of the piston.

Thus, the definitive resistance exerted against the piston consists of six resistances, which are: the friction of the waggons, the resistance of the air, the gravity of the train, the friction of the engine, the atmospheric pressure, and the pressure caused by the blast-pipe. Of these six resistances, the last two act immediately and directly on the piston. They must therefore be moved at the velocity of the piston itself; but it is not so with the other four. It has already been said that in an engine, the pressures exerted on different points by the same force, are in the inverse ratio of the velocities of those points. Here the engine and its train must

be moved at a velocity greater than that of the piston, in the proportion of the circumference of the wheel, to twice the length of the stroke. The intensity of the pressure exerted by the resistance of the load, the air, the engine, and the gravity, is then increased by its transmission to the piston, in the above ratio of the velocity of the wheel to that of the piston.

Consequently, if M express the number of tons gross which compose the total load, that is to say, including the weight of the tender-carriage of the engine, and k the number of pounds requisite to draw one ton on a railway,

$$k\,\mathrm{M}$$

will be the resistance, in pounds, resulting from the friction of the waggons which carry the load. If at the same time we call g the gravity of 1 ton on the inclined plane to be traversed by the engine, and if m represent the weight of the engine, in tons,

$$g\,(\mathrm{M} + m)$$

will be the resistance, in pounds, produced by the gravity of the total mass, train and engine; so that, according as the motion takes place in ascending or in descending, the definitive resistance arising from friction and gravity will be

$$k\mathrm{M} \pm g\,(\mathrm{M} + m) = (k \pm g)\,\mathrm{M} \pm gm.$$

Similarly, if we express by $u\,v^2$ the resistance, in pounds, exerted by the air against the train, at the velocity v of the engine,

$$(k \pm g)\ \mathrm{M} \pm gm + uv^2$$

will be the resistance opposed to the motion of the engine by the friction, the gravity, and the shock of the air.

If, again, F represent the friction of the unloaded engine, expressed also in pounds, and δ its additional friction, measured as a fraction of the resistance, as has been indicated in Chap. VIII., we see that

$$\mathrm{F} + \delta\ [(k \pm g)\ \mathrm{M} \pm gm + uv^2]$$

will be the total friction of the engine at the moment when it draws the resistance

$$(k \pm g)\ \mathrm{M} \pm gm + uv^2.$$

Consequently

$$(1 + \delta)\ [(k \pm g)\ \mathrm{M} \pm gm + uv^2] + \mathrm{F}$$

will be the total resistance opposed to the progression, along the rails, by the engine and its train.

As this force produces on the piston a resistance augmented in the ratio of the circumference of the wheel to twice the stroke of the piston, if D express the diameter of the wheel, l the length of the stroke, and π the ratio of the circumference to the diameter,

$$(1 + \delta)\ [(k \pm g)\ \mathrm{M} \pm gm + uv^2]\ \frac{\pi \mathrm{D}}{2l} + \frac{\pi \mathrm{DF}}{2l}$$

will be the resistance on the piston, caused by that force, that is to say, caused by the resistance of the waggons, the gravity, the air, and the friction of the engine.

This resistance is that which is exerted on the totality of the area of the pistons. But representing by d the diameter of the cylinders, $\frac{1}{2}\pi d^2$ will be the area of the two pistons. Whence

$$\frac{(1+\delta)\left[(k \pm g)\,M \pm gm + uv^2\right]\frac{\pi D}{2l} + \frac{\pi DF}{2l}}{\frac{1}{2}\pi d^2},$$

or, simplifying,

$$(1+\delta)\left[(k \pm g)\,M \pm gm + uv^2\right]\frac{D}{d^2 l} + \frac{DF}{d^2 l},$$

will be the same force, divided according to the unit of surface of the piston.

Adding to this the atmospheric pressure p, and the pressure caused by the blast-pipe $p'v$, which are already measured per unit of surface, we shall have in fine, for the *total* resistance R exerted on the piston,

$$R = (1+\delta)\left[(k \pm g)M \pm gm + uv^2\right]\frac{D}{d^2 l} + \frac{DF}{d^2 l} + p + p'v.$$

In this expression, the quantity g represents the gravity on the plane to be traversed by the train; if the plane be horizontal instead of inclined, we shall have $g = o$. The weights M and m of the train and the engine are expressed in tons gross; the quantity k, which is the friction of the waggons per ton, is equal to 6 lbs.; the value of δ is ·137 or $\frac{1}{7}$, for engines with uncoupled wheels; the velocity v of the engine is expressed in miles per hour; in fine, according as the dimensions D, l and d are expressed

in inches or in feet, and the forces u, p and p', in pounds per square inch, or in pounds per square foot, the value R which will result from the calculation will be the resisting pressure on the piston, expressed likewise in pounds per square inch, or in pounds per square foot.

Applying this calculation to a train of 9 waggons and a tender, weighing 50 tons gross, and drawn at the velocity of 20 miles per hour, up a plane inclined $\frac{1}{500}$, by an engine with two cylinders of 11 inches diameter, stroke of the piston 16 inches, propelling wheels 5 feet, not coupled, weight 8 tons, friction 104 lbs., blast-pipe 2·25 inches in diameter; and referring, for the resistance of the air, to what has been said in Chapters IV. and VI., the proceeding will be as follows:

$50 \times 6 = 300$ lbs.	Friction of the waggons, in pounds, or value of kM.
$\frac{2240}{500} \times 58 = 260$ lbs.	Gravity of the total mass, train and engine, or value of $g\,(M+m)$.
194 lbs.	Resistance of the air against an effective surface of 180 square feet, at the velocity of 20 miles per hour, or value of uv^2.
754 lbs.	Resistance of the train, or $(k+g)\,M+gm+uv^2$.

$754 \times 1{\cdot}137 = 857$ lbs. Resistance of the train, including the additional friction which it produces in the engine, or
$(1+\delta)\,[(k+g)M+gm+uv^2]$.

$+104$ lbs. Friction of the unloaded engine, or F.

———

961 lbs. Total resistance to the progressive motion of the engine, or value of the term
$(1+\delta)\,[(k+g)M+gm+uv^2]+F$.

On the other hand, we have

$3{\cdot}1416 \times 60$ in. $= 188{\cdot}5$ Circumference of the wheel, expressed in inches, or πD.

2×16 in. $= 32$ Double the stroke of the piston, expressed in inches, or $2l$.

$\frac{188{\cdot}5}{32} = 5{\cdot}9$ Ratio of the velocities of the wheel and the piston, or $\frac{\pi D}{2l}$.

Thus,

$961 \times 5{\cdot}9 = 5670$ lbs. Resistance produced on the piston, or value of the term

$$(1+\delta)\,[(k+g)M+gm+uv^2]\frac{\pi D}{2l}+\frac{F\pi D}{2l}.$$

Again,

$$\frac{3 \cdot 1416 \times 11^2}{2} = 190$$ Area of the two pistons, in square inches, or $\frac{1}{2}\pi d^2$.

Consequently, we obtain in fine

$$\frac{5670}{190} = 29 \cdot 8 \text{ lbs.}$$ Above-mentioned resistance, portioned per square inch of the surface of the piston.

$+ \; 3 \cdot 5$ lbs. Effective pressure per square inch, arising from the blast-pipe, or $p'v$.

$+ 14 \cdot 7$ lbs. Atmospheric pressure per square inch, or p.

$48 \cdot 0$ lbs. Definitive resistance, per square inch of the surface of the piston of an engine with two cylinders of 11 inches in diameter, &c., when drawing a load of 50 tons under the given circumstances.

Were it desired to know that resistance per square foot, it would suffice to multiply the last result by 144, that is to say, the pressure required would be 6912 lbs. per square foot, which number would have been obtained directly, if instead of expressing the area of the piston in square inches, and the partial

pressures in pounds per square inch, these measures had been referred to the square foot as unit of surface.

This example shows what is to be understood by the different quantities contained in the formula, and how each of them ought to be introduced into the calculation.

CHAPTER X.

OF THE VAPORIZATION OF LOCOMOTIVE ENGINES.

SECT. I. *Experiments on the vaporization of locomotive engines.*

So far our object has been to estimate the resistance offered to the motion of locomotives, according to the circumstances of their load and of their velocity. It will now be proper to value the power of which they can dispose to overcome that resistance; and as we have already made known the means of measuring one of the elements of that power, viz., the elasticity or pressure of the steam in the boiler, it remains only to seek what quantity of that steam can be produced by the engine in different circumstances, and in a given time.

For this purpose we undertook a series of experiments on the vaporization of locomotives, taking the engines successively either working without the aid of the blast-pipe, or with divers orifices of blast-pipe and different velocities, or, in fine, under different pressures in the boiler. We shall first give an account of these experiments, and then examine the influence of each of the circumstances

just mentioned, on the vaporization produced by the engine.

Among the experiments of which we are now going to present the results, the first three were made on engines at rest, and without the application of the blast-pipe, that is to say, without employing the waste steam in exciting the fire. The vaporization produced was therefore due simply to the natural draught of the chimney. In all the other experiments use was made of a blast-pipe, large or small, as will be seen indicated in the Table which we shall present further on.

To know the quantity of water vaporized by the boiler, the proceeding was this. As all the tender-carriages of the Liverpool and Manchester Railway, on which the experiments were made, have exactly the same dimensions, it was ascertained first of all, by weighing one of them when empty and when full, that every inch of depth of the water in the tank corresponded exactly to a weight of 206·5 lbs., or 3·304 cubic feet of water. This established, the next thing done was to ascertain, by means of the glass-tube, the depth of the water in the boiler at the beginning of the experiment, and at the same time the exact depth was taken of the water contained in the tank; afterwards, when the experiment was concluded, the boiler was first filled up to the height at which it was originally, and then the water remaining in the tank was measured. The difference between the two depths of water in the tank, gave

the consumption that had been made of it during the time of the observation.

As the experiments made with engines at rest, that is to say, without the application of the blast-pipe, show that in this state the engines are capable of effecting about $\frac{1}{5}$ of their vaporization with the aid of the blast-pipe, use has been made of this datum to take account, in the different experiments, of the vaporization which had taken place during the stoppages of the engine, and during the descent of the inclined planes, on which the engines run of themselves, without making use of the steam. It is evident, in fact, that during this time, as well as during the delays which took place on the road, the fire was no longer excited by the action of the blast-pipe, and the vaporization was necessarily reduced in consequence. As the experiments took place on the Liverpool and Manchester Railway, which has, in each direction, a declivity of the kind we have just mentioned, and the descent of which, with the use of the brake, is performed in 5 minutes, we have, in all the cases, taken 5 minutes for the duration of the suspension of the action of the blast-pipe relative to that circumstance. Thus, for instance, in experiment VI., the engine STAR stopped 15 minutes on the road. Besides this, the descent of the inclined plane occupied 5 minutes. Out of the total duration of the experiment, there were then 20 minutes during which the action of the blast-pipe was suspended. As, during this time, the engine

vaporized the same quantity of water that it would have done in 4 minutes, had it worked with the aid of the blast-pipe, it is plain that these 20 minutes of delay may be replaced by 4 minutes of forced vaporization. Thus the experiment is the same as if the 130·90 cubic feet of water consumed by the engine, had been vaporized in 1 hour 56 minutes of uninterrupted work; which gives 67·71 cubic feet for the vaporization effected per hour, during the application of the draught of the blast-pipe. In this manner the numbers contained in the last column but one of the Table, were deduced from the observations. It is to be remarked, that the delays which took place during these experiments were caused by various essays made on the engines.

To obtain the mean velocity of the motion, we divided the total distance performed, which was 29·5 miles, by the total time of the experiment, minus the delays which took place on the road; but in some experiments the engines ascended the inclined plane twice, which increased the total distance performed to 32·5 miles instead of 29·5; and in those cases we have taken account of that circumstance.

In all the experiments we give the pressure in the boiler from direct observation. In experiments I. and II. the boiler was not placed on the engine, and was open to the air, that is to say, the steam-dome and the cover of the man-hole were taken off; so that the vaporization went on under the

atmospheric pressure, or under an effective pressure null.

Before beginning any experiment, we waited till the steam made the valves blow, which showed that the vaporization was in full activity; and in the experiments I. and II., in which there was no valve, before beginning to note the quantity of water vaporized, we left the fire alight under the boiler for several hours, in order to be assured that the water effectually boiled in all its parts; and the non-fulfilment of this condition made us reject several experiments.

In fine, we give approximately the state of the temperature of the water in the tender, at the moment the engine started, because there must indubitably result from it an increase in the definitive vaporization of the engine; but as that temperature was not noted with sufficient accuracy, as it diminishes, moreover, during the experiment, and lastly, as it may easily be compensated by a superior quality in the fuel, or by more care on the part of the engine-man in stoking the fire, we are satisfied merely to point out its natural influence on the results, without seeking to take account of it with precision.

In the following Table, which presents the results of these experiments, we group together those engines in which there is sensibly a like proportion between the heating surface of the fire-box and that of the tubes. The object of this distinction will be

to seek, firstly, whether there results from it any difference in the vaporizing power of the engines in a given time; and again, whether there results therefrom any saving in the consumption of fuel in producing that vaporization. This second research will be the subject of the following chapter.

It will be remarked that the Table contains two different engines of the name of FIREFLY. The reason is, as we have said elsewhere, that on reconstructing that engine, the dimensions of the boiler had been changed, and it was proper therefore to distinguish the two engines by a different number. In like manner, the boiler under the name of GOLIATH II. was a new boiler, constructed to replace that which the engine had originally, and whose dimensions are given in the Table, page 37 of this work. The new boiler, however, of the Goliath, instead of being placed on the engine for which it had been made, was used as a stationary boiler at the Edge-Hill station, on the Liverpool and Manchester Railway. It was there that we submitted it to experiment, with the aid of Mr. Edward Woods, now the Company's engineer, who is well known to evince as much skill as care in whatever researches he undertakes.

Experiments on the vaporization of locomotive engines.

Number of the experiment.	Name of the engine.	Date of the experiment.	Heating surface. of the fire-box.	Heating surface. of the tubes.	Duration of the journey or of the experiment.		Delays on the road, not included in the preceding time.	Water vaporised during the experiment.	Average effective pressure during the experiment.	Velocity of the engine, in miles per hour.	Area of the blast-pipe.	Water vaporized per hour, delays deducted.	Water vaporized per hour, per sq. foot of total heating surface.	State of the water in the tender.
			sq. feet.	sq. feet.	h.	m.	minutes.	cub. feet.	lbs. per sq. in.	miles.	sq. inch.	cub. feet.	cub. foot.	
I.	GOLIATH II.	Aug. 18, 1836.	56·67	304·17	1	5	0	12·20	0	0	,,	11·26	·031	Cold.
II.	—	Aug. 19, 1836.	—	—	1	4	0	14·98	0	0	,,	14·06	·042	Cold.
III.	FIREFLY II.	Aug. 2, 1836.	46·74	270·63	1	3	0	12·39	50	0	,,	11·80	·037	Cold.
								Means . .	,,	,,	,,	12·37	·037	
IV.	STAR.	Aug. 13, 1836.	49·71	279·18	2	8	11	116·47	34·3	13·85	3·75	54·20	·165	Cold.
V.	—	Aug. 9, 1836.	—	—	2	15	35	153·64	45·1	14·45	3·13	68·79	·209	Very hot.
VI.	—	——	—	—	1	57	15	130·90	38·7	15·13	3·13	67·71	·206	Almost cold.
VII.	—	——	—	—	1	42	36	106·12	35·8	17·35	6·25	60·64	·184	Hot.
VIII.	—	Aug. 11, 1836.	—	—	1	41	22	110·26	,,	17·46	1·25	65·50	·199	Cold.
IX.	—	——	—	—	1	37½	15½	98·29	26·3	18·32	6·25	61·05	·186	Lukewarm.
X.	—	Aug. 13, 1836.	—	—	1	34½	5	95·82	27	18·79	2·50	62·83	·191	Hot.
XI.	—	Aug. 10, 1836.	—	—	1	25½	13	91·69	23·5	20·78	4·38	65·49	·199	Hot.
XII.	VESTA.	Aug. 1, 1834.	46·00	215·66	1	5½	0	66·08	51	27·23	4·91	66·00	·248	Very hot.
								Means . .	35·2	18·15	3·81	63·47	·198	
XIII.	FIREFLY I.	July 26, 1834.	43·91	317·71	1	35	5	98·29	44	17·70	3·98	64·10	·177	Almost cold.
XIV.	—	——	—	—	1	18	5	96·64	49	21·33	3·98	77·31	·191	Lukewarm.
XV.	FURY.	July 24, 1834.	32·87	267·84	1	35	0	87·14	57	18·68	3·65	57·46	·209	Cold.
XVI.	—	——	—	—	1	30	0	78·05	57	19·67	3·65	54·45	·181	Cold.
XVII.	LEEDS.	Aug. 15, 1834.	34·57	267·84	1	35	0	95·82	54	18·68	3·65	63·18	·214	Hardly tepid.
XVIII.	—	——	—	—	1	17½	3	85·07	49	21·99	3·65	68·82	·228	Very hot.
XIX.	VULCAN.	July 22, 1834.	34·45	267·84	1	17	3	74·34	54·5	22·99	3·65	63·60	·201	Hardly tepid.
								Means . .	52·1	20·13	3·75	63·70	·200	
XX.	ATLAS.	July 23, 1834.	57·07	197·25	3	2	15	132·16	53·7	8·99	6·78	43·81	·172	Cold.
XXI.	—	Aug. 4, 1834.	—	—	1	58	0	94·99	53	15	7·37	50·00	·197	Cold.
XXII.	—	July 31, 1834.	—	—	1	54	0	88·38	30	15·53	6·78	48·21	·190	Cold.
								Means . .	45·5	13·17	6·97	47·34	·186	

Sect. II. *Of the influence of the pressure in the boiler on the vaporization of the engine.*

In treating (Chapter II. of this work) of the laws which regulate the mechanical action of the steam, we have shown that the steam in contact with the liquid, under all degrees of tension, contains always the same total quantity of heat. Hence it follows, evidently, that to vaporize a given weight of water, under any pressure whatever, the same quantity of heat must always be communicated to it, that is to say, the same quantity of fuel must be consumed in the same boiler; and consequently too, a given consumption of fuel will always correspond to the vaporization of the same weight of water in the same boiler, whatever be the pressure under which that vaporization is effected.

To comprehend clearly how it is that the steam can be generated at a higher or lower degree of pressure by the same application of heat, we must consider what passes in the boiler during the ebullition of the water. Suppose a boiler filled with water to a certain level, and containing, above that level up to the dome of the boiler, a vacant space of 1728 cubic inches, capable of being filled with steam. Suppose, moreover, that the boiler be placed above a furnace filled with lighted coal, emitting a certain quantity of heat per minute. As soon as the fire shall have transformed into steam 1 cubic inch of the water contained in the boiler,

the steam thus generated will fill the vacant space just mentioned; and since we have supposed the capacity of that space to be 1728 cubic inches, that is to say, 1728 times the volume of the water vaporized, it follows that the steam which occupies that space will have a relative volume equal to 1728 times the volume of the water. Now, recurring to the Table which we havê given (Chapter II. of this work), and which is deduced from experiment, it will be recognised that, when the relative volume of the steam is expressed by the number 1728, the total pressure of that steam is then about 15 ℔s. per square inch, and its sensible temperature about 212 degrees of Fahrenheit. Thus, at this moment, the steam contained in the boiler will be at the pressure of 15 ℔s. per square inch. Supposing then the safety-valve to be loaded only with the atmospheric pressure, which is also very nearly 15 ℔s. per square inch, we perceive that, if the safety-valve is large enough, the pressure in the boiler will never rise above that point, because the steam will escape by degrees as it is produced; and consequently, whatever be the intensity of the fire, that is to say, in whatever quantity the steam be generated, it will still continue to be in the boiler at the pressure of 15 ℔s. per square inch, and at the corresponding temperature, or 212 degrees of Fahrenheit.

But if we suppose the safety-valve of the boiler to be loaded with 50 ℔s. per square inch, over and

above the atmospheric pressure, this is what will take place. At the moment when there is but one cubic inch of water vaporized, it will fill, as we have said, the vacant space in the boiler, and will be, as before, at the pressure of 15 ℔s. per square inch, and at the sensible temperature of 212 degrees. But, as the fire continues its action, the steam being no longer able to escape by degrees as it is produced, on account of the resistance of the valve, the vaporized water will accumulate in the boiler, that is, in the same vacant space of which we have given the capacity. When, therefore, 2 cubic inches of water shall be vaporized, since these 2 cubic inches will still occupy a space of 1728 cubic inches, it is plain that the volume of the steam compared to that of the water which produced it, that is, the relative volume of the steam, will be expressed by the number 864. Hence, from the same Table above mentioned, the steam resulting from the vaporization of these two cubic inches of water will be in the boiler at the total pressure of 31 ℔s. per square inch, and at the sensible temperature of 253 degrees, which corresponds to that pressure. As, however, the pressure of 31 ℔s. will not suffice to raise the valve and admit of the steam escaping by degrees as it is generated, the steam produced by the action of the fire will continue to accumulate in the boiler. When 3 cubic inches of water shall have been vaporized, the pressure in the boiler will be 48 ℔s. per square inch, and the tem-

perature 280 degrees; and, in fine, when there shall be 4 cubic inches of water transformed into steam, the pressure will have risen to 65 lbs. per square inch, and the temperature to 299 degrees of Fahrenheit. But at this moment the pressure of the steam will have become equal to the weight of the valve, and, in consequence, the latter will be raised. Whence, reckoning from this moment, and provided the safety-valve be large enough, the pressure and the temperature of the steam will continue to maintain themselves at the same degree, whatever may be the vaporization produced. But now, if we suppose that the fire retains in all cases a constant intensity, capable of communicating per minute to 1 cubic inch of water a quantity of heat expressed by 1170 degrees of Fahrenheit, or 650 degrees centigrade, we see that the boiler will be enabled to change 1 cubic inch of water into steam every minute, and that the cubic inch, thus transformed, will assume, according to the weight of the valve, 15 lbs., or 31 lbs., or 48 lbs., or, in fine, 65 lbs. per square inch. And each of these effects will be produced without it being necessary to suppose that the fire has acquired any more intensity, that is to say, without any more fuel being consumed in one case than in the other.

Thus it is seen that the vaporization resulting from a given consumption of fuel must always be sensibly the same, under whatever degree the steam in the boiler be generated. This, in fact, is con-

firmed by the experiments we have just presented. A slight advantage even is perceptible in those engines which work at higher pressure; for the GOLIATH II., working under the atmospheric pressure, vaporized on an average ·036 cubic foot of water per hour and per square foot of heating surface; and the FIREFLY II., under the effective pressure of 50 lbs. per square inch, instead of producing less, vaporized per hour and per square foot of heating surface, a quantity of water which amounted to ·037 cubic foot. The other examples offer similar results. For instance, in the two experiments V. and VI., the STAR, with the same blast-pipe and very nearly the same velocity, vaporized a greater quantity of water per hour under the pressure of 45 lbs. per square inch, than under that of 38·7; and we find the same result in the experiments XXI. and XXII. made with the engine ATLAS.

Considering the vaporization independently of the consumption of fuel, that is to say, seeking merely the quantity of water which the engines can vaporize per hour, without regard to the corresponding expenditure of fuel, we ought not to be surprised to find in general that the engines which work at a higher pressure produce a greater vaporization per hour. The reason is, that when the safety-valve of an engine is fixed, for instance, at 50 lbs. of effective pressure per square inch, it is less liable to blow, that is, to let the steam escape, than when it is fixed only at 40 lbs. of effective

pressure per square inch. In the latter case, then, the engine-man will see the valve blow more frequently, and this being for him a sign that his fire is as lively as need be, he will not serve the fire-box with the same activity; the result will be that he will indeed consume less fuel, but he will produce less vaporization per hour in the engine.

Thus, to recapitulate, we see that the vaporization in the engines is independent of the pressure in the boiler, and that even, when the vaporization is considered without regard to the corresponding expenditure of fuel, it is in general found more considerable under a high pressure than under a low one.

SECT. III. *Of the influence of the velocity of the engine on the vaporization of the boiler.*

It has been seen (Chapter VII.) that the pressure in the blast-pipe varies in the direct ratio of the velocity of the motion, and in the inverse ratio of the area of the blast-pipe. On the other hand, it is known that the draught which takes place in the fire-box is the result of the velocity assumed by the steam in the blast-pipe, and, consequently, in the chimney by reason of that pressure. It is natural then to think that the velocity of the engine and the size of the orifice of the blast-pipe must have an influence more or less considerable on the vaporization produced in the boiler.

In effect, on perusing the experiments which we have just presented, the influence of the velocity on the vaporization plainly appears; for, collecting the experiments made on the same engine and with the same blast-pipe, but with a different velocity, we form the following Table.

Experiments on the influence of the velocity of the engines on the vaporization of their boiler.

Number of the experiment.	Name of the engine.	Area of the blast-pipe.	Velocity, in miles per hour.	Vaporization per hour.	State of the water in the tender.
		sq. in.	miles.	cubic feet.	
{ V.	STAR.	3·13	14·45	68·79	Very hot.
{ VI.	—	—	15·13	67·71	Almost cold.
{ VII.	STAR.	6·25	17·35	60·64	Hot.
{ IX.	—	—	18·32	61·05	Lukewarm.
{ XIII.	FIREFLY I.	3·98	17·70	64·10	Almost cold.
{ XIV.	—	—	21·33	77·31	Lukewarm.
{ XV.	FURY.	3·65	18·63	57·46	Cold.
{ XVI.	—	—	19·67	54·45	Cold.
{ XVII.	LEEDS.	3·65	18·63	63·18	Scarcely tepid.
{ XVIII.	—	—	21·99	68·82	Very hot.
{ XX.	ATLAS.	6·78	8·99	43·81	Cold.
{ XXI.	—	7·37	15·00	50·00	Cold.
{ XXII.	—	6·78	15·53	48·21	Cold.

Comparing together those of the above experiments which were made with the same orifice of blast-pipe, and which we have, for that reason, united with a bracket, it appears that with the exception of the experiments V. and VI., XV. and XVI., in which, however, the change of velocity was quite inconsiderable, increase of velocity was

invariably attended with increase of vaporization; but the extent of that increase seems to have been modified by the temperature of the water in the tender. Thus in the experiments XIII. and XIV., as well as in the experiments XVII. and XVIII., the circumstance of the heat of the water in the tender has co-operated with that of the velocity to increase the vaporization, in the same manner as in the experiments V. and VI. that circumstance seems to have more than counterbalanced the then contrary effect of the velocity. It is only therefore by comparing together the experiments made with the engine ATLAS, that we can form a tolerably exact notion of the influence of the velocity on the vaporization. In effect, in the three experiments made with that engine, the heat of the water in the tender was the same; the blast-pipe had not perceptibly varied, and, with respect to the velocity, there was difference enough to give room to hope that other accessory circumstances would not be of weight sufficient to counterbalance its effect. The first of these experiments might then be compared to a mean taken between the two others; but as in the third, the safety-valve of the engine was designedly fixed at a very low pressure, viz., 30 lbs. per square inch instead of 50, and as that circumstance, by making the valve blow too easily, occasioned the engine-man not to keep up his fire with the same intensity as in the other experiments, we

shall have a more exact result by comparing only the experiments XX. and XXI.

Now, in the first, the engine, at the velocity of 8·99 miles per hour, vaporized 43·81 cubic feet of water, or ·172 cubic foot per square foot of heating surface; and in the second, the same engine, at the velocity of 15 miles per hour, vaporized 50·00 cubic feet of water, or ·197 cubic foot per square foot of heating surface. These numbers are almost in the precise ratio of the fourth roots of the velocities. We may therefore conclude that the vaporization, in locomotive engines, varies very nearly in the ratio of the fourth root of the velocity of their motion.

This variation is, as we see, of slight importance in the most ordinary cases; but when very great differences of velocity are concerned, like those, for instance, which take place in ascending inclined planes, where the velocity is often reduced to the half or the third of what it is on an average during the rest of the trip, we perceive that it then acquires a considerable influence, and consequently must not be omitted in the calculation. We shall take account of this effect in all the examples to be treated of in the sequel; but it is easy to see, at the same time, that in a great number of practical applications it may be dispensed with.

Sect. IV. *Of the influence of the orifice of the blast-pipe on the vaporization of locomotive engines.*

If attention be now directed to the effects of the blast-pipe, with reference to the vaporization, and if, with this view, the first series of the experiments already presented, in which no blast-pipe was used, be compared to the other series, in which, on the contrary, use was made of a blast-pipe more or less reduced in size, it will at once be observed that the application of the waste steam to the urging of the fire produces a very important effect, and that it nearly quintuples the natural vaporization of the boiler. But seeking afterwards what modification that effect undergoes from the narrowing more or less of the blast-pipe, we do not observe a very marked result in that respect.

Examining, for instance, the experiments made with the Star, in which the alterations in the orifice of the blast-pipe enable us to study its influence on the vaporization of the boiler, and referring, according to what has been said in the preceding section, the effects produced to the velocity of 20 miles per hour, we form the following Table.

Experiments on the influence of the diameter of the blast-pipe on the vaporization of boilers.

Number of the experiment.	Area of the blast-pipe.	Vaporization per sq. foot of total heating surface, at the velocity of 20 miles per hour.	
	sq. inches.	cub. foot per hour.	
VIII.	1·25	·206	·200
X.	2·50	·194	
V.	3·13	·227	·206
VI.	3·13	·221	
IV.	3·75	·181	
XI.	4·38	·197	
VII.	6·25	·191	·190
IX.	6·25	·190	

From these results, it appears that for this engine, of which the vaporization and heating surface have been given above, a blast-pipe of 3 to 4 square inches of area, or 2 to 2¼ inches in diameter, produces an average vaporization of about ·206 cubic foot of water per square inch of heating surface, per hour; that the contracting of the blast-pipe within 1·25 and 2·50 square inches, in nowise augments the vaporization, but even tends rather to diminish it; and in fine, that the enlarging of the blast-pipe to 6·25 square inches, produces a slight diminution of from ·206 to ·190 cubic foot of water per square foot of heating surface.

These effects will easily be explained, from the considerations which we shall offer in the next section, on the comparative vaporization of the

fire-box and the tubes of the boiler. It will then be at once perceived that, for a given surface of tubes, there needs a certain draught, that is, a certain aperture of the blast-pipe, to carry the flame to the very extremity of the tubes, so that the whole of their extent may receive the direct action of the flame. This result once obtained, a greater contraction of the blast-pipe or stronger draught, could only have the effect of carrying the flame beyond the extremity of the tubes, that is, into the chimney, where it would no longer influence the quantity of water vaporized. Diminishing, then, the orifice of the blast-pipe still more and more, beyond this point, would produce no change at all in the vaporization of the boiler, if the extreme contraction of the blast-pipe would not render at last the passage of the air through the fire-box so rapid that the greater part of it traverse the fire without being used for the combustion. This is an effect which manifested itself in our experiments; for during those which took place with a blast-pipe of 1·25 square inch of area, every stroke of the piston caused in the chimney a violent noise, somewhat resembling the report of a gun. It is readily conceived, then, that the contracting of the blast-pipe beyond certain limits, is productive of no advantage to the vaporization of the engine.

As to enlarging the blast-pipe too much, since it then ceases to supply a sufficient draught in the fire-box to carry the flame to the extremity of the

tubes, the remaining portion of these, beyond the point where the flame reaches, receives only the heat communicated by the contact of the hot gases resulting from the combustion already terminated; and the definitive vaporization must thereby be diminished.

This latter case carried to the extreme, would at last considerably reduce the vaporization, and consequently the effect of the engines; and this indeed is observed in practice, when a locomotive has been made with too large a blast-pipe, or when the latter has been corroded and widened by the effect of the fire; but as these defects are easily recognised and corrected, they are to be regarded only as momentary and exceptional. Hence, in the calculation of the effect of locomotives, we need consider but small variations in the diameter of the blast-pipe; and in such case, then, we see by the preceding experiments, that the change resulting in the vaporization of the engine is not of such importance as to require being introduced into the general formulæ of the motion of these engines.

Sect. V. *Of the comparative vaporization of the fire-box and the tubes, and of the definitive vaporization of the engines per unit of heating surface of their boiler.*

We have just inquired into the particular influence, which divers circumstances may have on

the vaporization of the engines: it now remains to examine the effects which may result in that respect from the construction of the boiler itself, or from the proportion that has been established between the heating surface of the fire-box and that of the tubes. We shall first seek then, how much of the total vaporization produced is attributable to each of these two portions of the boiler, and thence we shall afterwards conclude the definitive vaporization of the engines per unit of heating surface of their boiler.

The boiler of locomotives consists, as we have seen, of two distinct portions, one of which surrounds the fire-box, the other contains the tubes. The water contained in the portion which surrounds the fire-box, is every where in contact either with the ignited fuel, or with the flame which rises above that fuel. The water which surrounds the tubes, on the contrary, according to the intensity of the fire, and the length of the tubes, may be in contact, throughout the length of the tubes, either with the flame, that is to say, the ignited gases which issue from the fire-box, or partly with the flame and partly with the hot gases which are produced by the combustion. Now it is easy to conceive that the effect of the tubes will be very different in the two cases which we have just mentioned. If the tubes are in contact with the flame throughout their length, it does not appear that, comparing equal surfaces, they ought to produce

a vaporization less considerable than the fire-box; for the ignited gases which traverse them, are fuel as well as the coke itself, and it may be said that throughout their length they receive the immediate and radiating action of the fire. But if the combustion slackens in the fire-box, so that the flame extend only half-way along the tubes; that portion alone of the tubes will be really submitted to the radiating action of the caloric, and the rest will receive no more than the communicative heat arising from the contact of the still hot gases remaining after the combustion has ceased. Thus, in this case, the first half of the tubes may, with equal surface, produce as much vaporization as the fire-box, but the second half will necessarily produce a less effect, whence results that the mean vaporization of the tubes, per unit of their total surface, will then be less than that of the fire-box.

In a series of experiments which we undertook in 1836, at the station of the Liverpool and Manchester Railway, with Mr. Edward Woods, the Company's engineer, on a boiler originally made for a locomotive, but used in a stationary engine, and in which the two compartments were separated by a partition,—a circumstance which admitted of measuring directly the vaporization produced by the fire-box and by the tubes,—we, in fact, obtained results analogous to those which have just been indicated. The boiler was very long, and when the fire was left to itself, and the vaporization not

abundant, the tubes produced, comparing equal surfaces, an effect considerably less than the fire-box; but by degrees, on the combustion being more excited, and especially when, by means of a blast-pipe taken from an adjacent boiler, a more violent jet of steam was applied to the urging of the fire, the effect of the tubes differed less and less from that of the fire-box. As these experiments have not been quite conclusive, we shall not report them here, as to the precise results; but we mention the tendency of those results, in order to explain how, in an experiment on the same subject, an English engineer, operating on a small model, at rest, and without using the blast-pipe, could obtain for the proportion of the effect of the fire-box, to that of the tubes, the ratio of 3 to 1; and how, on the contrary, during the activity of the motion, with engines of the usual dimensions, and with the use of the blast-pipe, the two portions of the boiler may, if they are not too disproportionate one to the other, produce, per equal surface, equal effects, as we are about to see that it results from the preceding experiments, for the engines submitted to trial.

Referring, in effect, to the Table of page 253, in which the engines are divided into series, according to the proportions existing between the fire-box and the tubes, we perceive that, in the first and second series, the total heating surface is about 6·5 times that of the fire-box; in the third series, it amounts to 8·7 times that of the fire-box; and in fine, in the

fourth series, the total surface is but 4·5 times that of the fire-box. If then there were a considerable difference between the effect of the fire-box and that of the tubes, it would be found that in the engines wherein the fire-box forms a larger portion of the total surface, the effect produced per unit of surface would be greater. But, on the contrary, if we observe the means deduced from the last three series, we find that notwithstanding the diversity of proportion between the fire-box and the tubes, the vaporization per square foot of total heating surface remains always sensibly the same. We must then conclude, that during the active working of engines of a construction similar to that of the experiments, the two portions of the boiler vaporize, per unit of surface, the same quantity of water.

To know the vaporization of which a given engine is capable, it consequently suffices to measure the number of square feet composing its total heating surface, without distinction between the fire-box and the tubes, and then to multiply that number by the vaporization which each square foot of surface is capable of producing. It is then the latter quantity which we must now seek to determine; but, as we have seen that the vaporization produced per unit of surface varies with the velocity of the motion, it is necessary to specify at the same time the velocity at which we wish to measure the vaporization.

Now, referring to the experiments of page 253, we find that in the engines of the second series, the

vaporization per square foot of heating surface was ·198 cubic foot, at the velocity of 18·15 miles per hour. On the other hand, we know that the vaporization varies in the direct ratio of the fourth roots of the velocities. We may then deduce from thence, that at the velocity of 20 miles per hour, the vaporization of those engines will be

$$\cdot 198 \left(\frac{20}{18 \cdot 15}\right)^{\frac{1}{4}} = \cdot 203 \text{ cubic foot of water per square foot of heating surface.}$$

Operating in the same manner for the two following series, we obtain, for the velocity of 20 miles per hour, the determinations of the following Table.

Experiments on the vaporization of locomotive engines, per unit of total heating surface of their boiler.

Number of the series.	Average velocity of the engine, in miles per hour.	Vaporization per hour and per sq. foot of total heating surface, at the preceding velocity.	Vaporization per hour and per sq. foot of total heating surface, at the velocity of 20 miles per hour.
	miles.	cubic foot.	cubic foot.
2nd,	18·15	·198	·203
3rd,	20·13	·200	·200
4th,	8·99	·172	·210
4th,	15·26	·194	·208
		Mean . . .	·205

Thus, from these experiments, it appears that at the velocity of 20 miles per hour, the vaporization

of locomotives may be valued at ·205, or, in round numbers, at ·2 cubic foot of water per hour, per square foot of total heating surface of their boiler; and it appears also that the different engines and different velocities lead to numbers almost identical, which tends to confirm the valuation we have just obtained.

This determination is, as we have said, suitable to the velocity of 20 miles per hour; but it is easy to deduce from it that which would take place at any other velocity, by multiplying by the fourth root of the ratio between the given velocity and the velocity of 20 miles.

Such then will be the vaporization of an engine in motion, or, more properly, of an engine in which the blast-pipe is used. But if the engine is stopped, and the action of the blast-pipe interrupted in consequence, the first series of experiments presented page 253, proves that the vaporization per unit of heating surface then reduces itself, on an average, to ·037 cubic foot of water per hour, that is to say, to about a fifth of what it is at the velocity of 15 or 20 miles per hour. Thus, it will be possible, in all cases, to estimate the quantity of water reduced to steam by a given engine, in a determined time.

It is to be remarked, that were the vaporization of engines considered as composed of two parts, namely, the vaporization at rest, which is constant, plus a variable augment depending on the velocity; it would then be deduced from the preceding ex-

periments, that this variable portion changes in the ratio of the cubic roots, and not in that of the fourth roots of the velocities. But as, in reality, it is not the absence of velocity in the engine, but the interruption of the action of the blast-pipe, which produces the observed decrease of vaporization, during the moments of rest of the engines, it appears more accurate to consider these two effects of the engine, with or without blast-pipe, as entirely distinct from each other. Thus we will say that the engine, at rest or in motion, but without blast-pipe, vaporizes about ·037 cubic foot of cold water per hour, per square foot of total heating surface; but that, the action of the blast-pipe once introduced and regulated by the velocity, the vaporization will vary according to the fourth root of the latter, and that at the velocity of 20 miles per hour, the vaporization will be ·205 cubic foot of water per hour, per square foot of total heating surface.

It must however be observed, with respect to these determinations, that they are strictly suitable only to boilers constructed in proportions not very different from those used in the experiments; that is to say, according to what has been explained above, that the heating surface of the fire-box ought not to be under a tenth of the total heating surface of the boiler, and the orifice of the blast-pipe not much larger than we had it in our experiments, according to the adopted practice. Were any notable change made in this respect, were the coke

of an inferior quality, or the engine materially different in construction from what we have described, there would be grounds for a new determination of the vaporization.

In fine, we will again add, that the numbers obtained above indicate rather the consumption of water of the boiler, than the real *vaporization* produced; for we shall presently see, that out of the total water thus expended by the engine, there is a portion which is drawn into the cylinders, mixed with the steam, but without being itself vaporized. Consequently, to obtain the real vaporization of the engine, it will be necessary to take account of this circumstance, as we shall do further on.

SECT. VI. *Of the loss of steam which takes place by the safety-valves, during the work of locomotive engines.*

Among locomotive engines there are a great number which are subject to a continual loss of steam by the safety-valves. This effect arises from the engine being designedly constructed with an excess of power; that is to say, that according to the production of steam which takes place in its boiler, the engine could draw its regular load at a greater velocity than it is allowed to do. The result is, that to prevent the engine from acquiring too great a velocity, it becomes necessary partially to close the regulator, that is, to diminish the passage

of the steam, till no more enters the cylinder than the quantity necessary to produce the desired velocity. Then the surplus accumulating in the boiler, at last raises the safety-valve and escapes into the atmosphere. When this loss takes place only on the regulator being somewhat closed, it is but a proof, as we have said, of a surplus of power which the engine holds in reserve. But if it takes place more or less under all circumstances, then it depends on the steam-ways being too narrow, and is consequently a defect in the engine; in either case, however, it is necessary to obtain a valuation of this loss.

There is yet another case in which engines are subject to a loss of steam by the valves; but this loss is owing to a different cause from the preceding, and exhibits itself much more abundantly: it is when the engine ascends a steep acclivity, with an apparently moderate load, or when it ascends a moderate inclination, with a very heavy load. At these moments the valves are always seen to emit an enormous quantity of steam. The reason is that, as soon as the engine reaches the inclined plane, its load instantly becomes extremely heavy, on account of the surplus of traction required by the gravity on the plane. It has been shown, in effect, that on a plane inclined $\frac{1}{100}$, every ton produces, by gravity alone, a resistance equal to that of 3·7 tons on a level. It happens therefore, at that moment, that the resistance of the train may become greater than

the actual pressure of the safety-valve. Consequently the steam, instead of flowing by the cylinder, driving back the piston, raises the safety-valve, and escapes into the atmosphere. If then the passage which the steam thus opens for itself were sufficient for its total efflux, no more steam would pass through the cylinder, and the engine would inevitably stop. But we have already said, in speaking of safety-valves, that they are held in place by a spring which exerts a resistance by so much the greater as it is more compressed. The safety-valve then, being raised by the steam, acquires more and more pressure, and thus there will occur a point when that pressure becomes sufficient to keep the train in motion on the plane. The steam at this moment is free to escape at once by the safety-valve and by the cylinder, and divides itself between the two issues, in proportion to the orifices offered by them. Consequently the motion of the train then continues, but on condition that the steam shall preserve this accidental pressure; that is to say, that the valve shall still remain at the same point of elevation, or in fine, on condition that a considerable portion of the steam shall be lost in the atmosphere. This loss might be greatly diminished, by momentarily increasing the pressure of the safety-valve, so as to put it in equilibrio with the resistance which the train on the inclined plane produces against the motion; but as it might happen, if the engine-men were allowed this facility,

that they would use it inconsiderately and to the detriment of the engine, a collar is usually fixed on the rod of the spring-balance, which hinders the nut from being tightened beyond a certain point. This loss therefore is inevitable, whenever the definitive resistance produced by the train exceeds the extreme pressure thus fixed on the engine.

We are now about to consider in turn the two wastes of steam of which we have just spoken.

To obtain some estimation of the quantity of steam which escapes by the safety-valve, during the regular work of locomotives, we had recourse to the following method. During the whole continuance of the experiments on vaporization, which we have just presented, we noted the point at which the valve began to rise, and carefully observed the mean point at which it stood by the effect of the blowing of the steam. The interval between these two degrees gave the rising of the valve during the experiment, a rising in virtue of which the issue of the steam took place. Thus it will presently be seen that in experiment XII., the valve of the VESTA, fixed at 20 degrees of the balance as the starting point, rose on an average to 21·3 degrees by the blowing of the steam. The rising of the valve, or the passage constantly opened to the steam, during the experiment, was therefore 1·3 degrees measured on the balance.

On the other hand, when the regulator of the engine was designedly closed, the whole of the

steam generated in the boiler was forced to escape by the safety-valve. Observing then how many degrees the valve rose, we could recognise the number of degrees which corresponded to the total production of steam in the boiler. Comparing then the first rising with the second, that is to say, the partial opening of the valve, which took place in the regular work of the engine, with the opening capable of allowing the total issue of the steam, we could estimate the loss under consideration, as a portion of the total steam produced in the boiler.

In the following Table we have collected the observations made on this head, first during the experiments on vaporization already given, and afterwards while the regulator was totally closed. With respect to the number of degrees which represent the total issue of the steam in different engines, it will be conceived that this number depends firstly on the quantity of steam produced by each boiler; again, on the diameter of the valve, which, for a same degree of rising, may allow a greater or less passage to the steam; then on the dimensions of the levers and the size of the divisions of the balance, which make a degree of that balance correspond to a more or less considerable rising; and lastly, on the state of the second safety-valve of the engine, which may itself give more or less issue to the steam, or may not give it issue at all.

Experiments on the habitual waste of steam which takes place by the safety-valves of locomotive engines, during their regular work.

Number of the experiment.	Name of the engine.	Rising of the valve, in degrees of the balance, observed during the experiment.	Rising of the valve, in degrees of the balance, sufficient to give issue to the totality of the steam formed during the complete close of the regulator.
XII.	VESTA.	1·3	3·5
XIII.	FIREFLY I.	0	3
XIV.	—	·7	3
XV.	FURY.	1·5	5
XVI.	—	1·4	5
XVII.	LEEDS.	1·2	5
XVIII.	—	2·0	5
XIX.	VULCAN.	1·5	5
XX.	ATLAS.	·7	4
XXI.	—	·1	4
XXII.	—	1·5	4
		11·9	46·5

From this Table it is seen that the rising of the valve which took place in the experiments was, in degrees of the balances, 11·9 out of 46·5, that is to say, it amounted to nearly a fourth of the total steam produced during the total close of the regulator. Now, during the close of the regulator, the steam produced by the engine no longer passes to the cylinders, and consequently ceases to urge the fire in the fire-box; and we have seen that during

the suspension of that artificial excitation of the fire, the engine produces scarcely a fifth part of its vaporization during the work. It is therefore to be concluded from the preceding experiments, that in the engines submitted to observation, the loss of steam by the valves might be valued approximatively at $\frac{1}{20}$ of the total steam produced in the boiler during the motion of the engine.

The loss which has just occupied our attention is in some sort permanent during the work of the engines, and among all those which we have submitted to experiment, the STAR, whose passages for the circulation of the steam are very large, is the only one that was exempt from it. It will be necessary then to take account of this circumstance, for all engines liable to it, during the whole continuance of the work of the engine.

As to the loss which now remains to treat of, and which is occasioned in ascending steep acclivities, it takes place in all engines; but it is merely accidental, and need not be taken into consideration except in calculations that may be relative to the traversing of those planes. To obtain an approximate valuation of this loss, we used the same mode as in the preceding research: we attentively observed the engines of the Liverpool and Manchester Railway, while ascending, without an auxiliary engine, the planes of *Sutton* and *Whiston*, inclined $\frac{1}{89}$ and $\frac{1}{96}$, and the acclivity of *Chatmoss*, inclined $\frac{1}{1300}$, and noted the rising of their valves which took

place. The following Table contains the result of those observations, compared as before with the rising capable of giving issue to the whole of the steam produced in the boiler during the complete close of the regulator.

Experiments on the accidental loss which takes place by the safety-valves of locomotive engines, while ascending planes considerably inclined.

Name of the engine.	Weight of the engine.	Load of the engine, tender included.	Inclination of the plane.	Velocity of the engine, in miles per hour.	Rising of the valve, in degrees of the balance, observed during the ascent of the plane.	Rising of the valve, in degrees of the balance, sufficient to give issue to the totality of the steam produced during the complete close of the regulator.
	tons.	tons.		miles.		
Vesta.	8·71	33·15	$\frac{1}{89}$	14·11	2·50	3·5
Fury.	8·20	48·80	$\frac{1}{89}$	15·00	4	5
Fury.	8·20	56·16	$\frac{1}{98}$	6·31	3	5
Leeds.	7·07	35·15	$\frac{1}{89}$	10·00	1	5
Vulcan.	8·34	39·07	$\frac{1}{89}$	11·42	5	5
Atlas.	11·40	195·5	$\frac{1}{1800}$	8·00	1·75	4
Atlas.	11·40	40·15	$\frac{1}{89}$	7·50	2·50	4
					19·75	31·5

From these experiments, it is visible that when, by reason of an excessive load on a moderate inclination, or of an ordinary load on a steep acclivity, the engines are called upon to work at a pressure higher than that fixed by their safety-valve, they are liable to a variable loss, but which here on an

average amounts to $\frac{19 \cdot 75}{31 \cdot 5}$ of the steam produced by the boiler during the close of the regulator. And as we have shown that the latter vaporization is $\frac{1}{5}$ of that which takes place during the action of the blast-pipe, that is, during the progression of the engine, the above loss may be represented by

$$\frac{19 \cdot 75}{31 \cdot 5} \times \tfrac{1}{5} = \tfrac{1}{8} = \cdot 12$$

of the total vaporization produced by the engine during its motion.

It is conceivable, however, that the extent of this accidental loss must vary under different circumstances, and that it depends on the diameter of the valves, the length of the levers, the elasticity of the spring of the balance, and above all on the excess of the momentary resistance of the train above the pressure at which the safety-valve of the engine is regulated. For this reason, in calculations wherein precision is required, it will be necessary, as much as possible, to take account of it from direct observation for every engine.

Sect. VII. *Of the water drawn into the cylinders in its liquid state, and of the effective vaporization of the engines.*

There exists another loss much more important than the preceding, and to which locomotive engines

are particularly subject, by reason of the continual jerks which they undergo in their motion, of the little elevation of the entrance of the steam-pipe above the level of the water, of the small space reserved to the steam for its accumulation, and of the exceeding rapidity with which the steam issues from the liquid in the boiler. This loss consists of a considerable quantity of water drawn into the cylinders in its liquid state, and mixed with the steam, but without being itself vaporized. To conceive how this effect is produced, it suffices to observe the enormous quantities of water which are held in suspension in the air, in the form of clouds, and borne about by the wind. As, moreover, the steam which is produced in the boiler of locomotives is of a density much greater than that of the air, and as instead of touching merely the surface of the liquid, it disengages itself from the very middle of that liquid, one need not be surprised that it draws along with it a very considerable mass of water; and this effect will naturally be produced during the whole time of the work of the engine.

To obtain a valuation of the loss which occurs in locomotives from this cause, we, either by augmenting the load, or by lowering the pressure, or by choosing inclined portions of the road to traverse, placed the engines in such circumstances that the pressure of the steam in the cylinder could differ but very little from the pressure in the boiler; and we then compared the velocity really produced, with

that which ought to have been produced, had the totality of the water expended by the engine been really converted into steam. The difference between the water corresponding to the actual velocity of the engine and the total water expended during the motion, showed the quantity of water carried in its liquid state into the cylinders with the steam.

The cases in which the engine works at a pressure in the cylinder sensibly equal to that of the boiler, have already been pointed out; they are those wherein the engine reduces its velocity till it becomes impossible to admit that the steam can increase in volume, and consequently diminish in pressure on entering the cylinder, since such an increase of volume, slight as it might be imagined to be, would necessarily bring with it a greater velocity of the engine than the velocity observed. Now in performing for the different experiments which we are about to report, the calculation necessary to compare the real velocity of the engine with the velocity which ought to correspond to the total expenditure of water of the boiler, it will be recognised that in those experiments, the pressure of the steam in the cylinder could not be sensibly less than the pressure in the boiler; and this fact will again be found verified on performing, in the manner developed in Chapter IX., the calculation of the resistance then exerted by the load against the piston, a resistance which we shall see equal to the pressure of the steam in the cylinder.

To show how the calculation has been performed in the following experiments, we will give it in detail for the first of them. In this experiment, the engine ATLAS, expending 43·81 cubic feet of water per hour, at the average velocity of 8·99 miles per hour, assumed on an inclined plane and with a considerable load, a velocity of 8·00 miles per hour, working at a total pressure of 69·7 lbs. per square inch in the boiler. As the engine was then moving only at 8 miles per hour, whereas its mean vaporization of 43·81 cubic feet of water had been observed at the velocity of 8·99 miles per hour, and as it has been shown that the vaporization of engines varies as the fourth roots of the velocities, we see, firstly, that its vaporization during the portion considered of the experiment, must have decreased to 42·55 cubic feet.

On the other hand, the safety-valve of the engine, observed at the same moment, was raised 1·75 degrees of the balance, and in the engine ATLAS, an elevation of 4 degrees of the balance suffices, as has been said above, to give issue to the whole of the steam that the engine can produce while at rest. The loss of steam by the safety-valve was therefore

$$\frac{1{\cdot}75}{4} = {\cdot}4375$$

of the vaporization of the engine at rest. Now it has been shown that the vaporization while at rest is ·037 cubic foot of water per hour, per square foot

of total heating surface; and referring to the Table, page 37, Chapter I., we see that the total heating surface of the ATLAS is 254·31 square feet. Hence the loss of steam which took place by the safety-valve during the ascent of the plane, was

$$\cdot 4375 \times \cdot 037 \times 254 \cdot 31 = 4 \cdot 12 \text{ cubic feet per hour.}$$

Consequently the effective vaporization of the engine, at the same moment, was

$$42 \cdot 55 - 4 \cdot 12 = 38 \cdot 43 \text{ cubic feet per hour.}$$

But since the pressure in the boiler, at the moment of the experiment, was 69·7 lbs. per square inch, and the relative volume of the steam at that pressure is 407 times that of the water, it is clear in the first place, that admitting the steam to have been expended in the cylinder at the pressure of the boiler, which is the greatest pressure it can be supposed to have, it would have produced a volume of

$$407 \times 38 \cdot 43 = 15641 \text{ cubic feet.}$$

On the other hand, as the diameter of the cylinders of this engine is 1 foot, and the stroke of the piston 16 inches or 1·33 foot, the two cylinders augmented by $\frac{1}{20}$ for the vacant spaces filled by the steam at each stroke, but not traversed by the piston, offered a capacity of

$$2 \cdot 199 \text{ cubic feet.}$$

Such then was the volume of steam expended at each stroke of the piston. But since the engine

moved at a velocity of 8 miles or 42240 feet per hour, with a wheel of 5 feet in diameter, or 15·71 feet in circumference, it follows that it performed in an hour 2689 turns of the wheel, and consequently gave 5378 strokes of the piston in both the cylinders. The volume therefore of steam which it expended was but

$$5378 \times 2{\cdot}199 = 11827 \text{ cubic feet.}$$

Now, we have seen that supposing the steam to have had in the cylinder the same pressure as in the boiler, it would already have produced a volume of 15641 cubic feet, and every supposition of a smaller pressure for the steam carries with it the necessity of a volume still greater. Consequently, it is impossible to admit that the steam can have expended itself in the cylinder at a lower pressure than in the boiler.

Moreover, since, supposing even the steam in the cylinder at the same pressure as in the boiler, which is the most favourable supposition we can make, it still happens that the volume of steam expended by the cylinder is less than the volume of steam generated in the boiler, a part of the water must have been carried from the boiler to the cylinder, in its liquid state; and the comparison between the quantity of water consumed by the boiler and that which, in the state of vapour, corresponds to the velocity of the piston, shows that the quantity of water really converted into steam, is to the total quantity of water consumed, in the ratio of the numbers

$$\frac{11827}{15641} = \cdot 76.$$

Thus, in this experiment, we see that ·24 of the water expended by the boiler was carried into the cylinders without being reduced to steam, or that the *real* vaporization of the engine was ·76 of the total water expended.

For the other experiments, we give in the following Table all the elements of the calculation, which is performed in a manner entirely similar, except that in the experiments made with the engine STAR, on the acclivity of $\frac{1}{1800}$, no blowing of the safety-valve took place, which dispenses with introducing a reduction in that respect.

It will be observed that if, in any one of these experiments, we had committed an error in admitting that the pressure in the cylinder was the same as in the boiler, it would then follow that the quantity of water carried in its liquid state with the steam, would have been greater than our determination gives it, for that experiment. Consequently, we are sure that the result which we have obtained is not exaggerated.

It will be remarked, again, that the loss here observed in the engines, cannot be attributed to the partial condensation of the steam in the steam-ways and cylinders, because the position of these in the smoke-box, where they are in continual contact with the flame of the fire-box, renders that supposition quite inadmissible.

Experiments on the quantity of water carried in its liquid state, into the cylinders of locomotive engines, during their work.

Name of the engine.	Diameter of the cylinder.	Stroke of the piston.	Diameter of the wheel.	Weight of the engine.	Average velocity of the engine, during the trip.	Average vaporization of the engine, during the trip.	Load of the engine, tender included.	Inclination of the road.	Total pressure in the boiler.	Velocity of the engine on the inclined plane.	Rising of the valve, while ascending the inclined plane.	Rising sufficient to allow the total escape of the steam, produced by the engine at rest.	Vaporization of the boiler, deducting the loss by blowing, during the ascent of the plane.	Effective vaporization.	Ratio of the effective vaporization, to the vaporization of the boiler.
	inches.	inches.	feet.	tons.	miles per hour.	cubic feet per hour.	tons.		lbs. per sq. inch.	miles per hour.	degrees of the balance.	degrees of the balance.	cub. ft. per hour.	cub. ft. per hour.	
ATLAS.	12	16	5	11·40	8·99	43·81	195·5	$\frac{1}{1800}$	69·7	8·00	1·75	4	38·43	29·06	·76
—	—	—	—	—	15·53	48·21	40·15	$\frac{1}{89}$	65·7	7·50	2·5	4	34·31	25·78	·75
STAR.	14	12	5	11·20	15·13	67·71	120·27	$\frac{1}{1800}$	55·9	15·24	0	..	67·71	46·28	·68
—	—	—	—	—	13·85	54·20	109·68	$\frac{1}{1800}$	52·2	12·63	0	..	52·96	35·96	·68
VESTA.	11·125	16	5	8·71	27·23	65·00	33·15	$\frac{1}{89}$	69·7	14·11	2·5	3·5	48·23	44·05	·91
FURY.	11	16	5	8·20	19·67	54·45	56·16	$\frac{1}{96}$	80·2	6·31	3	5	34·30	21·90	·64
VULCAN.	11	16	5	8·34	22·99	60·60	39·07	$\frac{1}{89}$	72·2	11·42	5	5	39·69	35·91	·90

These results make known the quantity of water carried in its liquid state, with the steam, in the engines submitted to experiment. When we shall present (Chapter XII.) a series of observations on the velocity and load of locomotives, it will appear that two experiments made with the engine STAR, on the plane inclined $\frac{1}{89}$, would equally have furnished, for that engine, a determination of the quantity of water carried with the steam; but as, in these two cases, the rising of the valve took place without being observed, and as it could have been estimated only approximatively, we deemed it proper to prefer the two experiments of the Table, on the plane inclined $\frac{1}{1300}$, because there was then no loss by the valve, which removed all error in this respect.

Among the engines which we submitted to experiment, as will be seen further on, there are two, the FIREFLY and the LEEDS, in which we have not been able to determine the quantity of water carried with the steam. The reason of this is, that the former being then in a bad state of repair, and losing water by the tubes, was never in a condition to work with a heavy load. As to the second, it once ascended the plane inclined $\frac{1}{89}$ with a load of 35·15 tons, and must have worked at full pressure in the cylinder; but as this engine, when its regulator was quite open, was liable to *prime* considerably, that is, to fill its cylinders with water in a liquid state, and then to throw that water through the chimney in the form of rain, it was never made

to work but with the regulator partially closed. On the other hand, when ascending the plane inclined $\frac{1}{89}$, the regulator had been entirely opened, in order not to impede the work of the engine. It was then found to lose a great deal more water than in the ordinary course of its work. This experiment, then, could only determine the quantity of water carried in a liquid state, in an exceptional case, and not in the regular working state of the engine. The other engines not being liable to the effect we have just mentioned, did not offer the same difficulty.

The results which have just been presented above show that the quantity of water carried away with the steam, varies in different engines, and ought to be determined for each separately; but as, in taking the means between the different experiments, that loss is found to amount to ·24 of the total vaporization of the boiler, this proportion may be adopted approximatively for engines that have not been directly submitted to experiment in this respect; that is to say, in order to have the *effective* vaporization of a locomotive, the total vaporization of which its boiler is capable, must be first measured; from the result must be subtracted, if necessary, the loss, either accidental or permanent, which may be observed at the safety-valves, and the remainder must be multiplied by the fraction ·76. Thus will be obtained the volume of water which passes into the cylinder, in the real state of steam, and produces the motion of the piston.

This average determination may serve for engines not submitted to the experiment, as the LEEDS and the FIREFLY; but for those which have been the object of a particular determination, the latter ought of course to be employed, because the quantity of water carried with the steam evidently depends on the peculiar construction of each engine, and especially on the space reserved for the steam to form and accumulate in the boiler. If, in effect, that space is but ten times the capacity of the cylinder, it is clear that, at every stroke of the piston, a tenth of the steam generated will pass into the cylinder, and the density of the remaining steam will thus be found all at once reduced to nine-tenths of what it was before. This great change of density will immediately demand from the liquid, a new quantity of steam to replace that which is gone; but it is evident that the new steam will emerge from the liquid with so much the more violence, and consequently will draw by so much the more of that liquid with it, as it shall rush into a more rarified medium. If then the space reserved to the steam in the boiler contain 100 cylinders-full of steam, instead of 10, as the difference of density produced at each stroke of the piston will be but $\frac{1}{100}$, instead of $\frac{1}{10}$, the quantity of water carried away with the steam will be by so much less considerable. This is a fact well known in practice; for engines are observed to be much more liable to *prime* when the boiler is full, than when it is moderately filled. In locomotive

engines, the space left to the steam for its formation, consists of the top part of the boiler, and what is called the *steam-dome*. Clearly then, a boiler too small, or a steam-dome too confined, tends to augment the effect under consideration.

Moreover, if the entrance of the steam-pipe is but little elevated above the surface of the water of the boiler, and if it has a large diameter, the result must naturally be, that the steam will the more easily be raised to the entrance of the pipe, and be received into it in greater abundance. This is why some engines are subject to *priming* when their regulator is quite open, which depends on the orifice of the regulator; and were the inquiry as to the quantity of water carried with the steam susceptible of sufficient precision, it is probable that in all engines that quantity would be found somewhat greater in the cases wherein the regulator is entirely open, than in those wherein it is but partially so.

The quantity of water carried with the steam must then vary according to the peculiar construction of the engines; but it is yet again influenced by circumstances independent of the construction. Thus, when a very active fire is made in the fire-box, as there is then produced in the boiler a very considerable vaporization for the quantity of water it contains, and as, in consequence, there results a current of steam, through the liquid, by so much the more violent, it is conceivable that the water

carried with the steam must augment at the same time. In like manner, foulness of the water, forming at the surface a scum which the steam blows and traverses continually, must produce a similar effect; and, in fine, the higher the pressure in the boiler, the more easily the steam must carry the liquid water with it.

From what has just been seen, the carrying away of water in a liquid state takes place in the engines without any external sign of it being manifested, because the water mixed with the steam dissipates itself with it in the air. But there are moments when this effect is so violent, that it exhibits itself externally in a very evident manner. This occurs when the boiler is too full, or when, in order to set the engine in motion, the regulator is opened suddenly, instead of being opened by degrees. At such times is seen immediately to fall from the chimney an actual rain, which in practice is expressed by saying that the engine is *priming*. In the first case, the quantity of water carried with the steam evidently proceeds from the diminution of the space left to the steam for its formation. In the second, it proceeds from the opening of the regulator giving all at once a considerable issue to the steam, whilst the cylinders and pipes are then but slightly warm, and filled with a steam extremely rarified. The steam at that moment accumulated in the boiler is therefore in a manner carried off suddenly, and

in the agitation caused by the rapid formation of the new steam, a great quantity of water is carried with it.

The extent of the loss which has just occupied our attention, explains how some boilers expend water so rapidly that it is impossible to keep them full, even at a very moderate velocity, and how it has sometimes happened that by merely changing the steam-dome of an engine, a considerable reduction has been made in its expenditure of fuel. For this reason there is room to think that as the construction of locomotives shall advance towards perfection, this loss will diminish, and consequently the consumption of fuel which attends it will diminish at the same time. It is however to be observed, that the loss of fuel resulting from this defect is not in proportion to the loss of water itself; because the latter being carried off from the boiler in a state of liquid, carries with it only the *sensible* heat indicated by the temperature of the boiler, whereas, the rest of the water being carried off in the state of steam, carries with it, besides, the *latent* heat necessary to its existence in the state of an elastic fluid.

CHAPTER XI.

OF FUEL.

Sect. I. *Experiments on the consumption of fuel necessary to produce, in locomotive engines, a given vaporization.*

Before passing on to the calculation of the effects of locomotives, there is still another element of that calculation which it is indispensable to consider; namely, the quantity of fuel necessary to produce, in locomotive engines, a given vaporization.

In order to arrive at the determination of this element, during the experiments presented above, and which had for their object to make known the vaporization of the boiler, we carefully noted also the corresponding quantity of fuel consumed. To that end, the tender was first completely emptied of all the remaining fuel, the coke then accurately weighed and put into the tender. The fire-box was besides filled with coke to the level of the lower part of the door. At the end of the experiment, the fire-box was filled anew to the same height, and what coke remained in the tender was weighed with the same care as before starting.

In all the experiments the fuel employed was

coke of the best quality, or Worsley coke, which is prepared expressly for foundries. When the engines use that which is obtained from the gas-works, they consume about 12 per cent. more, exclusively of the loss arising from the friability of that fuel. It has moreover been found that the sulphurous parts contained in it are particularly destructive to metals, and for that reason the Liverpool and Manchester Railway Company have completely renounced the use of it, notwithstanding its moderate price. The smoke emitted by the combustion of coal prevents its being usually employed in locomotives, and therefore we have made no researches as to the use of that fuel.

The experiments of which we are about to give the results were made on the Manchester and Liverpool Railway. To take account of the delays which occurred on the road during the trip, and of the descent of the inclined planes with the regulator shut, we employed the same method as for the vaporization. That is to say, since experience shows that the consumption of fuel in the engines, while at rest or without the action of the blast-pipe, is about the fifth of their consumption while in motion, we have replaced the time of suspension of the action of the blast-pipe by the fifth of that time, which we have then added to the time of the effective progression of the engine; and it is by the total time thus found that we have divided the fuel expended, to deduce therefrom the consumption of fuel per hour of motion.

Experiments on the quantity of fuel consumed in locomotive engines, to vaporize a given quantity of water.

Number of the experiment.	Name of the engine.	Heating surface		Duration of the trip or of the experiment.		Delays on the road, not included in the above time.	Water vaporized during the experiment.	Coke consumed during the experiment.	Average effective pressure in the boiler, during the experiment.	Average velocity of the engine, in miles per hour.	Area of the blast-pipe.	Water vaporized per hour, delays deducted.	Coke consumed per hour, delays deducted.	Coke consumed per cubic foot of water vaporized.	State of the water in the tender.
		of the fire-box.	of the tubes.												
		sq. feet.	sq. feet.	h.	m.	minutes.	cub. ft.	lbs.	lbs. per sq. in.	miles.	sq. in.	cub. feet.	lbs.	lbs.	
I.	GOLIATH II.	56·67	304·17	1	5	0	12·20	86	0	0	,,	11·26	79	7·1	Cold.
II.	—	—	—	1	4	0	14·98	152	0	0	,,	14·06	143	10·1	Cold.
III.	FIREFLY II.	46·74	270·63	1	3	0	12·39	120	50	0	,,	11·80	114	9·7	Cold.
										Means	. .	12·37	112	9·0	
IV.	STAR.	49·71	279·18	2	8	11	116·47	1431	34·3	13·85	3·75	54·20	666	12·3	Cold.
V.	—	—	—	2	15	35	153·64	1456	45·1	14·45	3·13	68·79	652	9·5	Very hot.
VI.	—	—	—	1	57	15	130·90	1369	38·7	15·13	3·13	67·71	708	10·5	Almost cold.
VII.	—	—	—	1	42	36	106·12	1409	35·8	17·35	6·25	60·64	805	13·3	Hot.
VIII.	—	—	—	1	41	22	110·26	1248	,,	17·46	1·25	65·50	741	11·3	Cold.
IX.	—	—	—	1	37½	15½	98·29	1111	26·3	18·32	6·25	61·05	690	11·3	Tepid.
X.	—	—	—	1	34½	5	95·82	920	27	18·79	2·50	62·83	603	9·6	Hot.
XI.	—	—	—	1	25½	13	91·69	1133	23·5	20·78	4·38	65·49	809	12·4	Hot.
XII.	VESTA.	46·00	215·66	1	5½	0	66·08	774	51	27·23	4·91	65·00	761	11·7	Very hot.
							Means	. . .	35·2	18·15	3·81	63·47	715	11·3	
XIII.	FIREFLY I.	43·91	317·71	1	35	5	98·29	879	44	17·70	3·98	64·10	639	10	Almost cold.
XIV.	—	—	—	1	18	5	96·64	870	49	21·33	3·98	77·31	696	9	Tepid.
XV.	FURY.	32·87	267·84	1	35	0	87·14	746	57	18·62	3·65	57·46	492	8·6	Cold.
XVI.	—	—	—	1	30	0	78·05	806	57	19·67	3·65	54·45	562	10·3	Cold.
XVII.	LEEDS.	34·57	267·84	1	35	0	95·82	897	54	18·63	3·65	63·18	592	9·4	Scarcely tepid.
XVIII.	—	—	—	1	17½	3	85·97	690	49	21·99	3·65	66·82	560	8·1	Very hot.
XIX.	VULCAN.	34·45	267·84	1	17	3	74·34	664	54·5	22·99	3·65	60·60	541	8·9	Scarcely tepid.
							Means	. . .	52·1	20·13	3·75	63·70	583	9·2	
XX.	ATLAS.	57·07	197·25	3	2	15	132·16	1596	53·7	8·99	6·78	43·81	520	12·1	Cold.
XXI.	—	—	—	1	58	0	94·99	1224	53	15·00	7·37	50·00	644	12·9	Cold.
XXII.	—	—	—	1	54	0	88·38	881	30	15·53	6·78	48·21	461	10·0	Cold.
							Means	. . .	45·5	13·17	6·97	47·34	551	11·7	

In examining these experiments, it will be proper first to distinguish the effects of the introduction of the blast-pipe itself, from the effects which are afterwards due to the more or less contraction of it.

The first three experiments, which were made without the application of the blast-pipe, prove that the fuel consumed per hour in a locomotive engine in which the waste steam is not employed to excite the fire, and consequently in a locomotive engine at rest, is but about a fifth of the consumption which takes place in the same engine, during the use of the blast-pipe, or during the progression of the train. This is the fact which we have just made use of to take account of the stoppages of the engines.

As soon as the blast-pipe is employed, the consumption of fuel per hour in the fire-box augments considerably, and consequently the corresponding vaporization. But comparing the first and second series of the preceding experiments, we perceive that the vaporization produced does not augment quite so fast as the consumption of fuel. In effect, in the second series, the ratio between the surface of the fire-box and the total heating surface is nearly the same as in the first series. There is room then to think, from what will presently be seen, that the consumption of fuel per cubic foot of water vaporized, would have been nearly the same in the two series, if the second had not taken place with the use of the blast-pipe. Whereas, we find that the consumption of fuel, which was only 9 lbs.

of coke per cubic foot of water in the first case, amounted in the second to 11·3 lbs. Hence we must then conclude that the introduction of the blast-pipe greatly aids the combustion, but that the definitive vaporization produced by the engine does not augment in an equal proportion; and we shall presently see the reason of it, viz., that when the consumption of fuel increases by the introduction of the blast-pipe, the heating surface, remaining the same, no longer preserves the same proportion with the quantity of fuel consumed.

Thus, at first, we see that the introduction of the blast-pipe leads to the result of increasing the consumption of fuel per hour in the fire-box, and likewise the vaporization of the boiler, though in a less proportion. But in seeking afterwards the influence of a greater or less contraction of the blast-pipe, we cannot clearly distinguish any very marked effects in that respect. There is room to think that the consumption of fuel per hour, at equal velocities of the engine, must be increased to a certain degree by the contraction of the blast-pipe, as we have said in treating of the vaporization; but this augmentation appears too slight to show itself in a decided manner. It is easily found compensated by accidental circumstances, of which it is impossible accurately to take account, such as the quality of the fuel employed and the care of the engine-man in stoking the fire; and we see definitively that, in practice, and regarding only the usual

variations of the blast-pipe, we may consider the consumption of fuel per hour as undergoing no sensible change with the size of the blast-pipe.

Sect. II. *Of the most advantageous proportion to establish between the fire-box and the tubes of the boiler, in locomotive engines.*

It is still to be remarked in the preceding Table, that the different engines are more or less economical with regard to fuel, in proportion to the corresponding vaporization; that is to say, they do not all consume the same quantity of fuel to produce the same vaporization. With this in view, we have divided the engines into several series, according to the ratio which exists in each of them between the heating surface of the fire-box and that of the tubes, or, which comes to the same, between the heating surface of the fire-box and the *total* heating surface of the boiler. In the engines of the first and second series, the total heating surface is about 6·5 times that of the fire-box; in the third series, it amounts to 8·7 times that of the fire-box; and in fine, in the fourth series, the total heating surface is but 4·5 times that of the fire-box. The means deduced from each series of experiments show the motive of this division; for, comparing them together, we form the following Table.

Experiments on the most advantageous proportion to be established between the fire-box and tubes, in locomotive engines.

Number of the series.	Average heating surface of the fire-box.	Average heating surface of the tubes.	Vaporization per hour.	Coke consumed per hour.	Ratio between the total heating surface, and that of the fire-box.	Coke per cubic foot of water vaporised.
	sq. feet.	sq. feet.	cub. feet.	lbs.		lbs.
IV.	57·07	197·25	47·34	551	4·46	11·65
II.	49·30	272·15	63·47	715	6·52	11·31
III.	36·74	282·09	63·70	583	8·68	9·18

We see by this Table that the consumption of fuel per cubic foot of water vaporized, is so much the less as the total heating surface offers a greater extent relatively to the fire-box; and this result is easily accounted for on observing that the less fuel is consumed in an engine whose heating surface does not vary, the more heating surface there is per pound of fuel consumed, and consequently the more completely absorbed by the liquid is the caloric developed by each pound of fuel. Thus, in the third series, the fire-box was of such dimensions, that the engine consumed only 583 lbs. of coke per hour, whereas in the engines of the second series, the fire-box could consume 715 lbs. of coke in the same time. On the other hand, in each of the two series the total heating surface offered to the action of the fire was nearly the same, namely, 320 and 321 square feet. The caloric developed by each

pound of coke was then received by a surface of $\frac{321}{715} = \cdot45$ square foot in the second series, and of $\frac{320}{583} = \cdot55$ square foot in the third; which explains the advantage of the latter on the score of economy. It is for the same reason likewise, that, in the first series, the engines without blast-pipe, though of similar proportions to those of the second series, have yet been more economical in their expenditure, because the absence of the blast-pipe having rendered the consumption of fuel, in those engines, less considerable for a like heating surface, the case became similar to that of the third series compared to the second.

Finally, a like effect is again recognisable in the comparison of the third and fourth series. In the latter, the quantity of fuel consumed was not greater than in the third series; but the heating surface exposed to receive the action of the fuel was only 254 square feet instead of 320; and a correspondent difference of economy has resulted for the production of the steam.

We may then at once conclude from what precedes, that the most economical locomotive engines are those whose heating surface is the greatest relatively to the consumption of fuel in the fire-box; and as, in the same system of construction of fire-boxes, and with the use of the blast-pipe, the consumption of fuel, that is, the capacity of the fire-box, may be regarded as sensibly proportional to its heating surface, it is visible that the most eco-

nomical locomotive engines, with respect to fuel, are those in which the total heating surface is greatest relatively to that of the fire-box.

From this remark, one should then be induced to increase more and more the surface of the tubes relatively to that of the fire-box; there would, in effect, be thus obtained a still greater and greater economy of fuel: but there is another condition yet more important in the use of locomotive engines than the saving of fuel; and that is, to produce the greatest possible quantity of steam with a boiler of a given size. Now, it is evident that by more and more augmenting the surface of the tubes, we should bring them at last to such an extent that the flame of the fuel could cover only a portion of them. Hence, from what has been said (Chapter X.), the vaporization of the boiler per unit of heating surface would lower at the same time.

This, in fact, is what is observed on the Great Western Railway. There are engines, on that line, in which the total heating surface is equal to 10·3 times that of the fire-box, and others in which the ratio between those two surfaces is carried so far as 11·3 and 11·6. In the first, the consumption of coke is 8·80 lbs., and in the second, 8·43 lbs. per cubic foot of water vaporized. But at the same time, the vaporization of the first, referred to the velocity of 20 miles per hour, is ·200 cubic foot of water per square foot of heating surface, as in the engines of the Table which we have presented

above, whereas in the second, the vaporization, referred to the same velocity, is no more than ·185 cubic foot of water per square foot of total heating surface. It is clear then that, in the latter, the saving of fuel is obtained only at the expense of the effect of the engine, whereas with the proportion of about 10·3 between the total heating surface and that of the fire-box, the expenditure of fuel is diminished, without the definitive vaporization of the engine undergoing any reduction.

These different effects are easily accounted for by the observations we have already made in treating of the vaporization; but we will dwell yet a moment on the subject, to endeavour to recognise what is the most advantageous proportion to establish between the heating surface of the tubes and that of the fire-box.

When the surface of the tubes amounts to but about 3 or 4 times that of the fire-box, as in the engines of the fourth series of our experiments, the engine consumed as much as 11·65 lbs. of coke per cubic foot of water vaporized, because the excess of coke burnt in the fire-box serves only to carry the flame beyond the extremity of the tubes, that is to say, into the chimney, where it ceases to influence the vaporization, and can produce no other effect but to destroy rapidly the parts of the engine with which it comes in contact. Increasing then the surface of the tubes to 8 or 9 times that of the fire-box, as in the engines of the third series, the

consumption of coke is reduced to 9·18 lbs. of coke per cubic foot of water vaporized, without the definitive vaporization of the engine being affected, because the change has done no more than remedy the loss of fuel above mentioned. Finally, by augmenting the surface of the tubes beyond 10 times that of the fire-box, a further reduction is obtained in the expenditure of fuel per cubic foot of water vaporized; because not content with employing merely the flame which rises from the fire-box, we turn to use also a part of the caloric carried with the gases resulting from the combustion effected. But the portion of the tubes which serves to utilize this latter portion of caloric, produces much less vaporization than the rest of the boiler, whence results that the definitive vaporization of the engine, per unit of total heating surface, is found reduced at the same time.

We have reason then to think, from the different experiments cited above, that with coke for fuel, and with the other circumstances of the work and the construction of the engines, the most advantageous ratio to establish between the total heating surface and that of the fire-box, would be nearly that of 10 to 1: since for a less proportion there would be increase in the expenditure of fuel, without increase of vaporization; and for a greater proportion, on the contrary, there would be reduction in the vaporization of the engine per unit of surface, which would incur the necessity of a larger boiler,

and consequently of a greater weight, which it is important to avoid.

In fine, to arrive at a general conclusion from the experiments which we have presented above, it appears that, according to the proportion of the fire-box to the total heating surface, the consumption of fuel in locomotive engines varies from 9·2 to 11·3 and 11·7 lbs. per cubic foot of *total* water vaporized; so that it may, on an average, be valued at

10·7 lbs. of coke, per cubic foot of total vaporization.

SECT. II. *Of the consumption of fuel necessary to draw a given load a given distance.*

The result which we have just obtained makes known the average quantity of coke consumed, in the engines submitted to experiment, to produce a determined vaporization; but what is necessary to be known, in practice, is the quantity of fuel necessary to draw 1 ton a mile. Specifying in each of the experiments above noticed, and in some others which we are about to add to them, the load then drawn by the engine, and taking account of the distance which that load was conveyed, we form the following Table, in which is seen the consumption of coke per ton per mile, which took place in each case.

In this Table we first give the weight of the load, the duration of the trip, and the delays which oc-

curred on the road; and as the Liverpool and Manchester Railway, on which the experiments were made, has, in each direction, besides divers less important acclivities, an inclined plane on which it is often necessary to have assisting engines, we give also the number of those engines which were employed to draw the trains to the top of the planes inclined $\frac{1}{89}$ and $\frac{1}{96}$. We afterwards give the pressure of the steam in the boiler, and the velocity of the motion. The following column shows the consumption of coke which took place during the experiment, first such as it was observed, that is, delays included, and then delays deducted. To make this deduction, we proceed as it has been explained in the preceding section, that is to say, we add to the real duration of the trip the fifth of the delays, and by the time thus calculated we divide the total consumption of fuel, in order to obtain the consumption of coke which took place per hour or per minute, during the activity of the motion. Then, as soon as we know the consumption of fuel per minute of active motion, we take the fifth of it, which gives the consumption of fuel of the engine per minute of rest; after which it is easy to conclude that which takes place during the delays. Consequently, in fine, subtracting this from the total consumption, we obtain the numbers inserted in the eleventh column.

From what has just been explained, we have all the elements of the experiments. Nothing remains

but to determine the quantity of work, in tons conveyed 1 mile, which has been executed in each case; and dividing the consumption of fuel, delays deducted, by the quantity of work done, we have the consumption of fuel per ton per mile, such as it is contained in the twelfth column. The following need no explanation.

To obtain the quantity of work performed by the engine in each case, we refer the reader to Sect. VI. Chapter XVII. It will there be seen that, by reason of the different inclinations which exist on the Manchester and Liverpool Railway, in order to obtain the quantity of work requisite for the draught of a train along the whole line, the following formulæ must be used, according as the train is going from Liverpool to Manchester, or from Manchester to Liverpool, and according as the passage of the inclined plane is performed with or without assisting engine:

From Liverpool to Manchester	without assisting engine	$30{\cdot}79\ M_1 + 206$
	with assisting engine	$30{\cdot}79\ M_1 + 318$;
From Manchester to Liverpool	without assisting engine	$36{\cdot}89\ M_1 + 292$
	with assisting engine	$36{\cdot}89\ M_1 + 404$.

In these formulæ, M_1 expresses the load of the engine in tons gross, tender *not* included; and the constant number added to each expression, represents the quantity of work consumed by the friction of the tender of the engine, and by the gravity of the engine and its tender, on the different acclivities of the line. In the case of assisting engines, the

constant number comprises moreover an addition of 112 tons conveyed 1 mile, which represents the gravity of the assisting engine and its tender, and the friction of that tender itself, on the inclined plane traversed by the engine.

These formulæ gave then the *total* work performed by the trip engine and the assisting engine united, for the conveyance of the train upon the line. But if it be desired to know the work done by the *trip* engine, taken separately, then, from each of the foregoing expressions, must be subtracted the work done by the assisting engine. Now, as this engine is always more powerful than the trip engine, it may be estimated that, during the common action of the two engines, that is, during the passage of the inclined plane, the assisting engine, over and above its own weight and that of its tender, draws $\frac{2}{3}$ of the load M_1.

On the other hand, we have said that the weight of the assisting engine and its tender consumes, during the ascent of the plane, a quantity of work expressed by 112 tons conveyed 1 mile on a level; and, recurring to Sect. vi. Chapter XVII., it will be found that the ascent of the load M_1 on the inclined plane, causes, with regard to friction and gravity, a quantity of work represented by $7{\cdot}18\ M_1$ tons 1 mile, $\frac{2}{3}$ of which are $4{\cdot}79\ M_1$ tons 1 mile. The total work performed by the assisting engine is therefore represented by

$$4{\cdot}79\ M_1 + 112.$$

Finally then, subtracting, for the cases of assisting engines, this quantity from the preceding formulæ, we have, for the quantity of work done by the trip engine, taken separately:

From Liverpool to Manchester	without assisting engine	$30{\cdot}79\ M_1 + 206$
	with assisting engine	$26{\cdot}00\ M_1 + 206$;
From Manchester to Liverpool	without assisting engine	$36{\cdot}89\ M_1 + 292$
	with assisting engine	$32{\cdot}10\ M_1 + 292$.

The result of these formulæ gives, in tons gross conveyed 1 mile, the work executed by the engine during the total trip along the line. By this result then ought to be divided the quantity of coke consumed by the engine, delays deducted, to conclude the consumption of coke per ton conveyed 1 mile. Performing this calculation, we find the numbers of the thirteenth column of the Table.

Experiments on the quantity of fuel consumed

Number of the experiment.	Date of the experiment.	Name of the engine, and place of starting.		Nature and weight of the load, in tons gross, tender not included.		Duration of the trip, delays not included.		Delays on the road.	Number of assisting engines, in ascending the inclined planes.
					tons.	h.	m.	min.	
VI.	Aug. 9, 1836.	STAR,	from Liv.	23 wag.	114·77	1	57	15	1
IV.	Aug. 13, 1836.	——	from —	22 wag.	104·18	2	8	11	1
V.	Aug. 9, 1836.	——	from Man.	35 wag.	69·55	2	15	35	0
VII.	Aug. 9, 1836.	——	from Liv.	20 wag.	90·80	1	42	36	1
VIII.	Aug. 11, 1836.	——	from Man.	15 wag.	55·74	1	41	22	1
X.	Aug. 13, 1836.	——	from —	9 wag.	42·98	1	34½	5	1
IX.	Aug. 11, 1836.	——	from Liv.	12 wag.	54·34	1	37½	15½	1
XI.	Aug. 10, 1836.	——	from —	12 wag.	38·15	1	25½	13	1
XXIII.	July 5, 1834.	VESTA,	from Liv.	20 wag.	92·75	1	42	5	1
XII.	Aug. 1, 1834.	——	from Man.	10 wag.	28·15	1	5½	0	0
XXIV.	July 16, 1834.	JUPITER,	from Man.	7 coach.	30·09	1	12	4	1
XXV.	July 16, 1834.	——	from Liv.	8 coach.	33·09	1	12	3	1
XIV.	July 26, 1834.	FIREFLY,	from Man.	8 coach.	36·40	1	18	5	1
XIII.	July 26, 1834.	——	from Liv.	8 coach.	36·40	1	35	5	1
XV.	July 24, 1834.	FURY,	from Man.	10 wag.	43·80	1	35	0	0
XVI.	July 24, 1834.	——	from Liv.	10 wag.	51·16	1	30	0	0
XVII.	Aug. 15, 1834.	LEEDS,	from Liv.	20 wag.	83·34	1	35	0	1
XVIII.	Aug. 15, 1834.	——	from Man.	8 wag.	32·01	1	17½	3	0
XXVI.	July 1, 1834.	VULCAN,	from Liv.	20 wag.	97·70	1	37	3	1
XIX.	July 22, 1834.	——	from Man.	9 coach.	34·07	1	17	3	0
XX.	July 23, 1834.	ATLAS,	from Liv.	40 wag.	190·00	3	2	15	4
XXVII.	July 9, 1834.	——	from —	25 wag.	123·13	1	48	12	"
XXI.	Aug. 4, 1834.	——	from —	25 wag.	122·64	1	58	0	2
XXVIII.	July 14, 1834.	——	from —	25 wag.	118·90	1	31	19	3
XXIX.	July 11, 1834.	——	from —	25 wag.	117·61	1	41	5	"
XXX.	June 28, 1834.	——	from —	25 wag.	113·90	1	50	5	"
XXXI.	July 16, 1834.	——	from —	20 wag.	94·66	1	25	23	2
XXXII.	July 17, 1834.	——	from —	15 wag.	65·40	1	27	3	1
XXII.	July 31, 1834.	——	from Man.	12 wag.	35·15	1	54	0	0
XXXIII.	July 17, 1834.	——	from —	13 wag.	25·30	1	26	3	0

y locomotive engines, in drawing given loads.

verage ffective ressure in the boiler.	Average velocity of the engine, in miles per hour.	Coke consumed during the trip, delays included.	Coke consumed during the trip, delays deducted.	Coke consumed per hour, delays deducted.	Coke per ton gross drawn one mile on a level, tender not included.	State of the water in the tender, at the starting of the engine.	State of the weather.	Observations.
bs. per q. in.	miles.	lbs.	lbs.	lbs.	lbs.			
38·7	15·13	1369	1322	708	·41	Almost cold.	Fair and calm.	
34·3	13·85	1431	1398	666	·48	Cold.	Fair and calm.	32 empty wag.—The engine ascended the plane in 2 turns.
45·1	14·45	1456	1358	652	·54	Very hot.	Fair and calm.	
35·8	17·35	1409	1302	805	·51	Hot.	Fair and calm.	
,,	17·46	1248	1182	741	·57	Cold.	Fair and calm.	6 wag. empty.
27·0	18·79	920	900	603	·54	Hot.	Fair and calm.	
26·3	18·32	1111	1064	690	·66	Tepid.	Fair and calm.	
23·5	20·78	1133	1084	809	·90	Hot.	Fair and calm.	
53	17·35	916	897	555	·34	Hot.	Calm.	
51	27·23	774	761	761	·57	Very hot.	Fair, wind fav.	5 wag. empty.
53	24·58	836	812	727	·65	,,	Fair, wind agst.	
53	24·58	742	721	645	·68	Almost cold.	Fair and calm.	
49	21·33	870	847	696	·58	Tepid.	Rainy, wind agst.	The engine in a bad state.
44	17·70	879	858	639	·75	Almost cold.	Fair.	
57	18·63	746	738	492	·39	Cold.	Fair, w. sideways.	
57	19·67	806	797	562	·45	Cold.	Fair and calm.	
54	18·63	897	887	592	·37	Hardly tepid.	Fair and calm.	1 wag. half the road.
49	21·99	690	675	560	·46	Very hot.	Fair and calm.	
54·5	18·25	1071	1048	684	·38	Tepid.	Calm.	
54·5	22·99	664	650	541	·42	Hardly tepid.	Fair, wind agst.	
53·7	8·99	1596	1561	529	·30	Cold.	Calm.	
53	16·39	1102	1071	624	·31	Tepid.	,,	Wheel connecting-rods too tight.
53	15·00	1224	1213	644	·36	Cold.	Fair and calm.	
61·5	19·45	1118	1057	737	·32	Cold.	Fair and calm.	
53	17·53	1136	1113	696	·34	Tepid.	,,	
53	16·09	1104	1084	619	·34	Rather hot.	,,	
53·5	20·82	1081	1005	754	·38	Rather tepid.	Calm.	
54	20·35	1012	988	723	·52	Very hot.	Fair and calm.	
30	15·53	881	873	481	·55	Cold.	,,	4 wag. empty.
54·5	20·58	720	703	520	·57	Very hot.	Fair and calm.	8 wag. empty.

Examining these experiments, we immediately recognise that the quantity of coke necessary to draw a ton 1 mile, is so much the greater as the load of the engine is less, or as the velocity is greater. We recognise at the same time, that this effect is not owing to an increase in the consumption of fuel per hour; for that consumption does not appear to undergo any regular change; the variations we observe in it, sometimes in excess, sometimes in diminution, being sufficiently explained by some accidental difference in the quality of the fuel, or in the assiduity of the engine-man in stoking the fire. But the difference noticed here is easily accounted for, on considering that the engine is obliged, besides its load, to draw its own weight and that of its tender, and to overcome divers constant resistances; and the quantity of fuel necessary to perform this work being then divided according to the number of tons in the load, becomes by so much the more sensible as the load itself is lighter. Thus it is that we see the same engine expending twice and almost three times as much coke, per ton per mile, in one experiment as in another.

It would therefore be inaccurate to draw an average result from the preceding Table, in order to apply it to the different cases that might occur. But if it be desired to know the quantity of fuel necessary for the engine per ton per mile, the load the engine is to draw must previously be given. Now, by

measuring the heating surface of the boiler, and recurring to the results obtained in Chapter X., the quantity of water which the engine is able to vaporize per hour will be known; and consequently, from the experiments presented in Section I. of the present chapter, the corresponding consumption of fuel will be deduced. Then, by the formulæ which will be developed in Chapter XII., the velocity of the engine with the given load on any inclination whatever will be determined. Therefore, if the railway in question be level, or if it consist of one uniform inclination, in multiplying the given load by the velocity the engine will assume with that load, the product will immediately make known, in tons conveyed 1 mile per hour, the useful effect of the engine. Dividing then the consumption of fuel of the engine per hour, by the useful effect produced in the same time, the quotient will give definitively the quantity of fuel which will be consumed by the engine, per ton per mile, in drawing the given load. This method will be a natural consequence of the very theory of the engine, as will be seen in Chapter XII., when we come to treat of the useful effect of locomotive engines, and for this reason we shall not dwell any longer upon it here.

If the railway in question, instead of being established on a uniform inclination, be composed of a series of ascents and descents, the velocity of the engine must be calculated on each of the

inclinations; and, by the process indicated in Sect. III. Chapter XVII., the total time of the trip will be determined. Consequently, since the consumption of fuel per hour is already known, that which will take place during the whole duration of the trip will immediately be concluded. Then, proceeding, as we have just done, to form the foregoing Table, or as will be explained Sect. VI. Chapter XVII., the work executed by the engine during the same trip will be obtained. Dividing then the expenditure of fuel by the work executed, the result will definitively be the quantity of coke, per ton per mile, expended by the engine, in drawing the given load, on the variously inclined railway in question.

CHAPTER XII.

THEORY OF LOCOMOTIVE ENGINES.

ARTICLE I.

OF THE EFFECTS OF THE ENGINES WITH AN INDEFINITE LOAD OR VELOCITY.

SECT. I. *Of the different problems which present themselves in the calculation of the effects of locomotive engines.*

THE principal problems which occur with respect to locomotive engines have reference in the first place to two circumstances, namely: I. When the engine is already constructed, and the question is to determine the effects that it will produce; II. When the engine is as yet unbuilt, and the question is to determine the proportions it ought to have in order to produce desired effects. At present we consider only the questions relative to the first case, and shall reserve the others for the following chapter.

When an engine is already constructed, and all its dimensions may be directly measured, the following problems may present themselves:

1st. To determine the velocity the engine will assume, with a fixed load;

2nd. To determine the load it will draw at a desired velocity;

3rd. To determine the useful effect it will produce, at a desired velocity or with a fixed load.

And this last problem may, itself, be expressed under ten different forms, namely, to find successively:

The useful effect of the engine, in tons drawn 1 mile;

The useful effect expressed in horse-power;

The quantity of fuel necessary per ton per mile;

The quantity of water necessary per ton per mile;

The useful effect produced per pound of fuel consumed;

The useful effect produced per cubic foot of water vaporized;

The consumption of fuel which produces 1 horse-power;

The consumption of water which produces 1 horse-power;

The horse-power produced per pound of fuel;

The horse-power produced per cubic foot of water vaporized.

Moreover, as two cases are necessarily to be distinguished in the work of the engines, namely, the case in which they work with a load or velocity *indefinite*, and that in which they work with the

load or velocity which produces the *maximum of useful effect*, there will yet occur in this respect a new series of questions, namely:

1st. To determine the velocity at which the engine will produce its maximum of useful effect;

2nd. To determine the load corresponding to the production of the maximum of useful effect;

3rd. To determine the maximum of useful effect that the engine can produce.

And this last problem may be expressed under the ten different forms which we have indicated above.

We will, then, consider successively these two series of questions.

SECT. II. *Of the elements to be considered in the calculation of the engines.*

In the attempts hitherto made for calculating the effects of steam engines, or for determining the velocity of the piston under a given load, the calculation has been grounded on two data only: the pressure of the steam in the boiler, and the resistance of the load against the piston.

This mode seems to comprehend all the data of the problem; but its erroneousness ought to have been recognised, when it was seen that all essays made to arrive at any formulæ by this means, produced nothing that was not annihilated by experience. It is more especially in endeavouring to

apply this method or these formulæ to the motion of locomotive engines, in order to determine the load they can draw at a given velocity, or the velocity they can assume under a given load, that the calculator is quickly led to results which are palpably inadmissible.

The cause of this appears in these two facts: 1st. That the pressure of the steam in the boiler, even supposing it to represent exactly the pressure in the cylinder, or the *effort* applied against the piston, would be far from offering, on that account, a complete measure of the power of the engine, that is to say, of the *motive force* of which it can dispose, and could not therefore be sufficient to calculate its effects: 2nd. That the pressure in the boiler does not represent the pressure in the cylinder, or the effort applied against the piston, but can only fix its extreme limits, that is to say, it can only indicate the maximum load of which the engine is capable, and nothing else. We shall here demonstrate the first of these points; the second will naturally be made clear when we come to treat of the pressure in the cylinder.

We say, that supposing the case wherein the pressure in the cylinder were equal to the pressure in the boiler, that is, the case in which, on measuring the pressure in the boiler, we should thereby obtain the effort applied by the engine, that measure would not suffice to make known its disposable motive force, nor consequently to calculate the

effects it can produce. In fact, when we consider an engine in a state of statical equilibrium, or at rest, the force which it applies reducing itself to a simple pressure, is found completely represented by the effort which the engine can exert, or by the mass which it can hold in equilibrium. But when we consider engines in a state of motion, the force which they apply is no longer a pressure, but a *motive force;* that is to say, it is no longer limited to the producing of an effort, but an effort and a velocity. This force, therefore, is no longer measured by the mass which it can hold in statical equilibrium, but by the mass which it holds in dynamical equilibrium, that is, in uniform motion, and by the velocity which it is capable of communicating to that mass. If then the effect of a steam engine were to be calculated in the state of equilibrium at rest, it might be sufficient to take account, in the calculation, of the pressure of the steam, which would make known the intensity of the effort applied; but as, on the contrary, it never occurs to compute the effects of these engines, except in a state of motion, it follows, that to estimate the motive force of which they can dispose, or to calculate their effects, we must at once take account of the effort applied by the engine, and of the velocity with which it can maintain that effort. Now, in steam engines, the pressure of the steam indicates only the mass which the engine can hold in equilibrium, and it is the velocity of the production

of the steam alone which indicates the velocity which the engine can communicate to that mass. Hence it is only by introducing these two elements into the calculation, that an exact valuation can be attained of the effects which will be produced.

The velocity of production of the steam is nothing more than the quantity of steam generated in a given time. Thus, the power of an engine resides at once in the greater or less quantity of steam which it produces, and in the degree of pressure or elastic force of that steam. In this valuation, the pressure is visibly no more than the means of verifying the state of the force, at the moment when in a manner its quantity is measured; and this explains why, in the statical equilibrium, that is, when no velocity is produced, and it therefore becomes useless to consider that quantity, the pressure suffices to represent the power; but it is otherwise in the state of motion, because then, as we have seen above, the pressure of the steam is but one of the elements to be considered.

We may besides obtain conviction, by more practical considerations, that the pressure of the steam in the boiler cannot suffice to determine the velocity of the engine with a given load. If, in effect, a locomotive engine be put to trial, weak as it may be on the score of vaporization, it is easy, by loading the safety-valve with 50 lbs. per square inch, to fill the boiler with steam at that effective pressure, or, which means the same, at the total pressure of 65 lbs.

per square inch. If then a load of 100 tons be attached to the engine, let which be the greatest load it can draw with an effective pressure of 50 lbs. per square inch, will it be said that the engine must necessarily draw that load at a certain fixed velocity which shall depend only on the pressure in the boiler and the resistance to the piston? Certainly not; for if it happen that the engine transform per minute 1 cubic foot of water into steam at the pressure of the boiler, it may, by that vaporization, produce a certain velocity; but if it vaporize but half that quantity, *cæteris paribus*, it clearly can fill the cylinder but half the number of times per minute. Thus the pressure in the boiler may remain the same; but the velocity of the engine, with the same load, must necessarily be reduced to half. It is plain, then, that the pressure in the boiler does not suffice to represent completely the power of the engine, or to make known its effects.

But if, by analogy with other boilers already tried, and by a comparison of the extent of heating surfaces, we previously estimate what quantity of steam, at a given pressure, a boiler is able to produce per minute; or if, with still more efficacy, we fill the boiler with water, and producing in the fire-box, by any means whatever, a fire as intense as it is in the usual work, we ascertain its vaporizing power; then alone we shall know the velocity at which the engine can continue its motive effort,

and be able to estimate the work it can perform in a given time.

The pressure of the steam in the boiler, taken alone, can determine but one thing: viz., the limit of the load of the engine, from the necessity which exists that the resistance against the piston should never exceed the pressure in the boiler, since the resistance would then be greater than the power, and consequently the motion could not be produced. But in every inquiry into which the velocity figures, recourse must necessarily be had to the vaporizing power; and then the separate influence of each of these two elements in the result is this:

The limit of the load possible for the engine is given by the degree of pressure in the boiler;

And the velocity with that load, or with any other, is given by the vaporizing power.

These effects will become much clearer as we shall develope the theory of the engine; but we thought it right to explain them here in a summary way, to show from what motive we entirely lay aside the ordinary mode of calculation applied to steam engines. Since the first edition of this work, we have published, under the title of *Theory of the Steam Engine*, a work in which we have developed at length the proofs of the inaccuracy of the processes in use for calculating the effects or the proportions of steam engines; to that work then we refer for whatever may not appear to be sufficiently explained here.

Sect. III. *Of the pressure of the steam in the cylinder.*

The pressure of the steam *in the cylinder* is the first inquiry that must engage our attention in order to be able to determine the effects of the engine. It is, in fact, always easy to ascertain the quantity of steam generated per minute in the boiler. If then we knew also the pressure at which that steam is expended in the cylinder, we might immediately conclude the velocity which the engine must necessarily assume; for it would suffice to divide the volume of steam produced, by the contents of the cylinder, to have the number of cylinders-full of steam, and consequently the number of strokes of the piston the engine will furnish per minute, which will give its velocity.

At a first glance, it is natural enough to think that the pressure of the steam in the cylinder must be the same as in the boiler, or at least that it must differ from it only according to the losses to which the engine may be liable; but it is easy to obtain conviction that such is not the case, and that in an engine subject to no loss of any kind whatever, the pressure in the cylinder, during the permanent motion, may at times be sensibly equal to that of the boiler, and at times much less; which depends, not on losses supported by the steam, but on the load drawn by the engine.

We know, in fact, that in every sort of engines the velocity, exceedingly small at first, increases by degrees up to a certain point, beyond which it does not go, because the mover is not capable of greater velocity with the mass which it has to move. If the engine is well constructed, and especially if it is regulated by a fly-wheel, that velocity, once attained, maintains itself without alteration, though the action of the mover may continue to vary, or, in other words, to oscillate between certain limits, and the motion becomes quite uniform.

As soon as the motion has attained uniformity, which always happens at the end of a short time, and which is the normal state of the engine during its work, the mover, which at the commencement of the motion must necessarily have exerted a force greater than the resistance, now expends but the force precisely capable of holding that resistance in equilibrium; for were it to apply a force greater or less, the motion would be accelerated or retarded, whereas by the fact it is uniform.

Now, in the engines under consideration, the force applied by the mover is nothing more than the pressure of the steam against the piston, or in the cylinder; as soon, therefore, as the engines have attained uniform or permanent motion, the pressure of the steam in the cylinder is strictly equal to the resistance of the load against the piston.

To account for the manner in which the equilibrium of pressure establishes itself in a locomotive

engine, it suffices to trace its effects from the origin of the motion. At that moment, the steam being enclosed in the boiler at a certain pressure, passes into the steam-pipes, and thence into the cylinders. Entering these, whose area is about 10 times that of the pipes, the steam at first dilates, losing proportionally its elastic force; but as the piston is not yet in motion, and as by reason of the load which it supports, it can acquire its velocity but very slowly, whereas the steam continues to arrive with rapidity, the equilibrium of pressure quickly establishes itself between the boiler and the cylinder; and the piston, driven by all the force of the steam, begins slowly to move in the cylinder. The motion thus impressed on the piston communicates itself therefore to the engine and to all its train, and the entire mass acquires a certain velocity. At this moment, if the arrival of the steam were suddenly intercepted, the piston would not stop on that account; it would, itself, be carried on for some time by the force which it has previously communicated to the moving mass. The result therefore is, that at the following stroke, the steam finds the piston already moving with a certain velocity, at the moment when it comes to impress a new quantity of motion thereon; and this new supply of motion passes on to the mass, where it continues to accumulate. Thus, receiving at every stroke a fresh impulse, and preserving the former one, the piston by degrees accelerates its motion, and the train at

last acquires all the velocity the engine is capable of communicating to it.

From what has just been said, we see that at the moment of starting, the slowness of the motion allows the steam to acquire in the cylinder the same pressure as in the boiler, and that it is the superiority of that pressure over the resistance of the piston which makes the latter more and more accelerate its motion, till at last it attains all the velocity which it is capable of acquiring with the resistance with which it is loaded. But as the piston assumes a greater velocity, it in a manner flies before the steam, without allowing it time to acquire in the cylinder all the pressure it might assume there. The action of the steam to accelerate the motion of the piston, becomes then less and less; and finally, when the piston has attained the greatest velocity the engine can communicate to it, the accelerating action of the steam upon it has become null, since it can augment its motion no more. Now, the accelerating action of the steam consists in the excess of its pressure above that of the resistance. Hence at this moment the pressure of the steam in the cylinder and that of the resistance against the piston, are precisely in equilibrium with each other; and if the motion of the engine remains in a state of uniformity, it is because the resistance which is exerted continually, and would have for effect to retard the motion, is immediately destroyed by an equal pressure from the

mover; whence results that the motion must continue the same without alteration.

In steam engines in general, the uniformity of motion is produced by a fly-wheel; but in locomotive engines, it is the mass of the train itself which performs the office of a fly-wheel. This mass receives and in a manner stores the quantities of motion impressed by the mover in its moments of greatest action, to restore them afterwards, when the mover is in a moment of less force; and it is from the very difficulty of increasing or diminishing the velocity of the mass, that the uniformity of motion of the whole results. With respect to certain parts of the engine, which, like the piston, for instance, must necessarily vary in velocity during the time of their oscillations, the uniformity of motion in question is understood to mean an exact conformity of time, such that at any point of one oscillation, the velocity is precisely the same as it was at the same point of the preceding oscillation; so that if the duration of one of these oscillations were taken for the unit of time, the motion would be strictly uniform.

We see then, from what precedes, that at the commencement of the motion or at the starting of the engine, the steam begins by acquiring in the cylinder a pressure equal to that of the boiler; but that this state is but transitory, and that as the velocity of the piston increases, the pressure in the cylinder gradually lowers, till at last it becomes precisely equal to the resistance of the load. This

equilibrium once established, the velocity of the piston ceases to increase, the motion becomes uniform, and the steam continues to expend itself in the cylinder at the pressure indicated by the resistance.

Thus, we know the pressure at which the steam expends itself in the cylinder; and knowing also the volume of the cylinder, we may conclude the absolute expenditure of steam which takes place at every stroke of the piston; wherefore, comparing this expenditure with the total mass of steam of which the engine can dispose, we may without difficulty deduce the velocity of the motion.

Sect. IV. *Of the velocity of the engine with a given load.*

We have just said that with the elements which we have at our disposal, we can determine the velocity which an engine will assume in drawing a given load.

Suppose, in effect, that a load of 50 tons gross, tender included, be drawn up a plane inclined $\frac{1}{500}$, by an engine with 2 cylinders 11 inches in diameter, stroke of the piston 16 inches, wheels 5 feet, friction 103 lbs., total pressure of the steam in the boiler 65 lbs., or effective pressure 50 lbs. per square inch, and, finally, vaporizing power nearly such as we have found it for the average of the Liverpool and Manchester locomotive engines, that is, 60 cubic feet of water per hour, or 1 cubic foot per minute.

We have already found above, Chapter IX., that the total resistance opposed by that load to the motion of the piston, in the case of this engine, is 48 lbs. per square inch, when the velocity is 20 miles per hour. If then we admit that the engine will come near enough to that velocity, for the valuation which we have made of the resistance of the air and the pressure caused by the blast-pipe, in the calculation, not to be very far from the truth, we must conclude that, during the uniform or permanent motion of the engine with that load, the pressure of the steam, during its action in the cylinder, will likewise be 48 lbs. per square inch.

Now the quantity of water consumed by the boiler amounts to 60 cubic feet of water per hour, and we have shown in treating of the vaporization, that out of that mass of water 75-hundredths only, on an average, are really converted into steam, and that the rest is merely carried away with the steam into the cylinders, but in a liquid state. The effective vaporization of the engine is then firstly

$\cdot 75 \times 60 = 45$ cubic feet per hour, or
$\cdot 75$ cubic foot per minute.

This water is first transformed, in the boiler, into steam at the total pressure of 65 lbs. per square inch; but on passing into the cylinders it acquires the pressure of 48 lbs. per square inch, and we know that, in this change, the steam remains al-

ways at the maximum density for its temperature. Its volume may then be determined by the Tables which we have given in Chapter II., on the volume of the steam formed under different pressures. According to these Tables, the volume of the steam formed under the total pressure of 48 lbs. per square inch, is 573 times that of the water which produced it. Hence the quantity of water effectively vaporized per minute in the boiler, will form during its passage through the cylinders, a volume of steam expressed by

$$573 \times \cdot 75 = 430 \text{ cubic feet.}$$

On the other hand, the area of each cylinder is 95 square inches, or in square feet that area is represented by ·66 square foot; and the stroke of the piston is 16 inches or 1·33 foot. Whence the capacity of each cylinder, traversed by the piston, is

$$\cdot 88 \text{ cubic foot.}$$

But, besides the portion traversed by the piston, there still exists, at each end of each cylinder, a vacant space called the *clearance of the cylinder*, which is necessarily filled with steam at each stroke. The capacity of this vacant space, represented by an equivalent portion of the cylinder, and steam-ways included, is usually $\frac{1}{20}$ of the part of the cylinder traversed by the piston. The real capacity, therefore, which is filled with steam at each stroke of the piston, is

$$\cdot 88 \times \tfrac{21}{20} = \cdot 924 \text{ cubic foot.}$$

Consequently the number of strokes of the piston which the engine will give per minute, by reason of its effective vaporization, will necessarily be

$$\frac{430}{\cdot 924} = 465.$$

Now each time the wheel makes one revolution, the engine gives two strokes of the piston in each of its two cylinders; and the diameter of the wheel is 5 feet, which makes 15·71 feet in circumference. Therefore at every 4 strokes of the piston, the engine advances 15·71 feet; that is to say, its velocity, in feet per minute, will be

$$\frac{465}{4} \times 15\cdot 71 = 1822 \text{ feet.}$$

Finally, as 1 mile contains 5280 feet, and 1 hour contains 60 minutes, the definitive velocity of the engine, in miles per hour, will be

$$\frac{60}{5280} \times 1822 = 20\cdot 71 \text{ miles.}$$

Thus we see that the above vaporization will necessarily produce a velocity of 20·7 miles per hour for the engine; that is to say, a locomotive engine with the given proportions may, if in good order and with a well-stocked fire, draw a load of 50 tons gross, tender included, up a plane inclined $\frac{1}{500}$, at the velocity of 20·7 miles per hour.

We shall, in the sequel, refer again to the pre-

vious valuation of the velocity of the engine, necessary to have the resistance of the air against the train, and to the variation of the vaporization. We only wished, at this moment, to show the mode of proceeding of the calculation.

With regard to the velocity which we have just obtained, we must add, that if the engine suffers, besides, a loss of steam by the safety-valve, which, as we have seen, takes place in a great number of locomotive engines, there will then be a corresponding loss on the effective vaporization; and consequently the definitive velocity of the engine will be reduced in a corresponding proportion. For instance, if the engine, like those of the Liverpool and Manchester Railway, be liable to a loss of ·05 of its vaporization in full activity, its definitive velocity, in the case above mentioned, will become

$$\cdot 95 \times 20{\cdot}71 = 19{\cdot}67 \text{ miles per hour.}$$

The calculation will be performed in the same manner for every other load and for every other engine. Thus, in general, resuming the notations precedently employed, in the inquiry upon the resistance on the piston, that is:

M, Representing the number of tons of the load, tender included;

m, The weight of the engine, in tons;

g, The gravity, in pounds, of one ton on the plane the engine has to traverse; this gravity being null for the case of a horizontal plane;

k, The friction of the waggons per ton, expressed in pounds;

v, The velocity of the engine, in miles per hour;

uv^2, The resistance of the air against the train, at the velocity v, resistance expressed in pounds;

$p'v$, The pressure against the piston, arising from the action of the blast-pipe, expressed in pounds per square foot;

F, The friction of the engine, in pounds;

δ, Its additional friction, measured as a fraction of the resistance, according to what was explained in Chapter VII.;

D, The diameter of the propelling wheels of the engine, in feet;

d, The diameter of the cylinder, in feet;

l, The length of the stroke of the piston, in feet;

c, The clearance of the cylinder, represented by an equivalent portion of the stroke of the piston, and consequently in feet;

P, The *total* or *absolute* pressure of the steam in the boiler, in pounds per square foot;

p, The atmospheric pressure, expressed in pounds per square foot;

Finally, S the *effective* vaporization of the engine, in cubic feet of water per hour, at the velocity known or unknown of the motion;

$$R = (1+\delta)[(k \pm g)M \pm gm + uv^2]\frac{D}{d^2 l} + \frac{DF}{d^2 l} + p + p'v$$

will be the pressure of the steam per unit of surface in the cylinder, as has been demonstrated above, Chapter IX.

On the other hand, if we express by μ the relative volume of the steam generated under the pressure R, a relative volume which will be found in the Tables given Chapter II.; since S is the volume of water vaporized per hour in the engine, it follows that

$$\mu S$$

will be the corresponding volume of the steam under the pressure R, that is to say, during its action in the cylinders.

But, expressing by π the ratio of the circumference to the diameter, the capacity of each cylinder which is traversed by the piston, has for its measure

$$\tfrac{1}{4}\pi d^2 l;$$

and the clearance of the cylinder offers, besides, a capacity of

$$\tfrac{1}{4}\pi d^2 c.$$

Therefore the totality of the space filled with steam at each stroke, in each cylinder, has for its expression

$$\tfrac{1}{4}\pi d^2 (l+c).$$

Consequently the number of strokes of the piston corresponding to the volume of steam expended μS, will be

$$\frac{\mu S}{\frac{1}{4}\pi d^2 (l+c)}.$$

But, while each piston performs 2 strokes, that is, at every expenditure of 4 cylinders-full of steam, the engine advances 1 turn of the wheel, that is to say, a space represented by

$$\pi D.$$

Therefore the velocity of the engine, in feet per hour, will be expressed by the above number of strokes, divided by 4 and multiplied by πD; that is to say, the velocity will be

$$V = \frac{\mu S}{d^2} \cdot \frac{D}{l+c}.$$

And finally, as 1 mile contains 5280 feet, the velocity of the engine, expressed in miles per hour, will be

$$v = \frac{1}{5280} \cdot \frac{\mu S}{d^2} \cdot \frac{D}{l+c} \cdot \quad . \; . \; . \; . \; . \; (1)$$

This expression will make known the velocity required, on substituting, for each of the letters, the value suitable to it in the engine considered.

As it has been shown, Chapter II., that the relative volume of the steam under the pressure R, may be expressed by

$$\frac{1}{n+q\,R},$$

it is plain that, instead of seeking the relative volume μ in the Tables which we have given, its value may be represented by the expression

$$\mu = \frac{1}{n+qR} = \frac{1}{n+q\left\{(1+\delta)\left[(k\pm g)M \pm gm + uv^2\right]\frac{D}{d^2l} + \frac{DF}{d^2l} + p + p'v\right\}};$$

and consequently the preceding expression of the velocity of the engine may equally be written under the form

$$v=\frac{1}{5280}\cdot\frac{1}{q}\cdot\frac{l}{l+c}\cdot\frac{S}{(1+\delta)\left[(k\pm g)M\pm gm+uv^2\right]+F+\frac{d^2l}{D}\left(\frac{n}{q}+p+p'v\right)} \quad \text{... (1 bis)}$$

Such then will be the general expression of the velocity of the engine, in miles per hour; an expression in which all is known from measures taken on the engine, even the vaporization S, which results from the extent of heating surface, according to what has been shown, Chapter X.

Making use of this formula to find the velocities corresponding to divers loads of the engine, or to divers values of M, attention must be paid never to suppose, for M, a load capable of producing on the piston a resistance greater than the pressure of the steam in the boiler, because it is evident that the resistance would then exceed the power, and the motion could not take place. This *maximum* load of the engine will form a special inquiry in Article II. of this chapter. Nor can M be supposed of a value less than the weight of the tender, which is the *minimum* load an engine can have to draw. Beyond these two limits the solutions given by the formula would evidently cease to suit the problem.

As to the velocity resulting from this formula, we shall equally see, in the following article of this chapter, that, for a given value of the vaporization S, it can never be less than a certain quantity which we shall determine, and which will consequently

make known the *minimum* velocity of the engine. With respect to the *maximum* velocity that the engine can attain, it clearly will depend principally on two things; the weight of the load, and the inclination of the plane on which that load is drawn. If we first suppose either an ascending inclined plane, or a horizontal plane, or an inclined plane descending, but on which the gravity does not exceed the friction of the train, it will be found that the less the load is, the greater velocity the engine will assume. If we suppose, on the contrary, a descending inclined plane, on which the gravity exceeds the friction of the train, it will be found that the more the plane is inclined, and the heavier the train is, the more the velocity of the motion will increase, because the excess of the gravity above the friction will be by so much more considerable, and that this force acts in favour of the motion. But it is not to be supposed that on a plane exceedingly inclined, or with a very heavy load, the velocity of the motion can ever increase indefinitely. The slightest essay of calculation on the preceding formula will immediately demonstrate this; and the reason of it will readily be conceived, on observing that by degrees as the gravity and the effort of the engine tend to augment the velocity of the train, the air opposes, on the contrary, more resistance, and a resistance moreover which increases in the ratio of the square of the velocity. We shall see, therefore, Chapter

XVII., that the engines, when descending inclined planes, assume much more moderate velocities than one would be tempted to admit at a first view.

It is to be remarked that the formula which we have just obtained for the velocity of the engine, still contains, in the second member, the two terms uv^2 and $p'v$, which are functions of v, and whose value cannot consequently be precisely found without knowing the velocity v itself, which is the quantity sought. Were it desired to disengage the unknown quantity entirely, those two terms must be eliminated from the second member of the equation; but to avoid the equation of the third degree which would then result, the formula may be used such as it is. In order to effect this, a probable estimation must first be made of the quantity v, and by means of it an approximation of the two terms uv^2 and $p'v$ will be furnished; then substituting these in the formula, a certain value of v will be deduced. If this value coincide with that which has been supposed to determine the two terms uv^2 and $p'v$, or at least differ from it only in an inconsiderable degree, it will be the true value of v, since it will completely satisfy the equation. If, on the contrary, the value of v thus found differ too much from that which has been supposed in the determination of uv^2 and $p'v$, for these two terms to be considered as having been properly estimated, the value of v obtained by this first calculation must be employed, to estimate with more precision the

two terms uv^2 and $p'v$; then, substituting them in the equation, a second value of v will be attained, more approximate than the first. This second value, should it not appear sufficiently exact, would serve in the same manner to find a third; but with a little practice in the calculation, two trials will always be found sufficient, and the recurrence of the same numbers will so simplify the research, that a third trial, in case of need, will be made without the least difficulty.

If it be wished to take account in the calculation of the variations which the vaporization of the engine undergoes by reason of the velocity, according to what has been shown, Chapter X., the given vaporization will be that which is known for a certain determined velocity, that is, it will be, for that velocity, the value of the quantity S then supposed variable. In this case, the same process must be used in determining S, as has just been explained for the quantities $p'v$ and uv^2. Thus, having made a previous estimation of the velocity, the corresponding values of S, $p'v$ and uv^2 must be deduced, and the equation solved with them. If the resulting value of v do not coincide with the supposition made, the latter must be corrected, as has been said above. This shall be illustrated further on by an example.

We have yet to observe that the value of v, in the equation (1 bis), or the expression of the velocity of the engine, is entirely independent of the pressure in

the boiler. This result has nothing surprising; for we have proved that the steam assumes, in the cylinder, a pressure strictly indicated by the resistance of the piston, and that moreover, in this change, the steam remains at the maximum density for its temperature, as if it rose immediately from the liquid at that very pressure. The consequence is therefore, that it matters little whether the steam has been originally produced in the boiler at any other greater pressure, since that pressure in the boiler is but a transitory state which ceases to subsist, and of which no trace remains, as soon as the steam begins its action. If, for instance, the resistance of the piston, and consequently the total pressure of the steam in the cylinder, is 50 lbs. per square inch, is it not true, that provided the steam be abundantly furnished at that pressure by the heating surface, it is quite indifferent whether till the moment of being used, it has been stored in the boiler under a pressure of 65, or 75, or 95 lbs. per square inch? That steam must always, definitively, at the moment of action, be transformed into steam at only 50 lbs. of pressure; and the velocity will depend solely on the quantity of steam at the pressure of 50 lbs., which shall have been furnished by the boiler. It is very erroneously then that engine-men are frequently seen to augment the pressure in the boiler of the engines, in the hope of obtaining a greater velocity. It is the vaporization, and not the pressure, that must be augmented, and it is very

probable that if the truth, in this respect, were more generally known, steam engines, and particularly those of steam vessels, would be liable to fewer explosions; for a great number of those accidents are to be attributed to the desire of obtaining a greater velocity, which the engine-man flatters himself of being able to attain by augmenting considerably the pressure in the boiler, by means of the safety-valves.

With regard to the quantities contained in the formulæ, we have indicated above the manner in which each of them ought to be expressed, and it will have been remarked that we have referred all the measures to uniform unities, namely: the foot, the pound, and the hour, as respective unities of length, weight, and time. The observation of this rule is absolutely indispensable, in order that the formulæ may be what is called *homogeneous*, and consequently that they give an exact result. This is a remark on which we deem it necessary to insist, because, in practice, some of the quantities which we employ are expressed in inches, others in pounds per square inch, or sometimes in atmospheres, &c., according as it may seem most commodious for common use; and if all these measures were not restored to homogeneity, none but a most erroneous result could be obtained.

In order however that no difficulty may occur on this head, we shall, in the sequel, resume this subject, in transforming the obtained formulæ into

practical formulæ, and shall then give an example of the application of each of them.

Lastly, before passing to another problem, we must yet remark that the formula which we have obtained above, differs in appearance from that which we have given for the same purpose, in the work entitled *Theory of the Steam Engine.* But the reason is merely that some of the terms in it are more developed, and, besides, that the velocity here calculated is that of the engine and not of the piston, which has obliged us to refer the different resistances, not to the velocity of the piston, as in the work just cited, but to the velocity of the engine expressed in miles per hour.

Sect. V. *Of the load of the engine for a desired velocity.*

The object of the preceding research was to determine the velocity of the engine for a fixed load. But if, on the contrary, the velocity be given, and that it be desired to know what load the engine can draw at that velocity, on a plane of a determined inclination, then it will suffice to resolve the equation (1 bis) with reference to M, and we shall have for the value of M,

$$M = \frac{1}{(1+\delta)(k \pm g)} \left[\frac{1}{5280} \cdot \frac{l}{l+c} \cdot \frac{S}{qv} - \frac{d^2 l}{D} \left(\frac{n}{q} + p + p'v \right) - F \right] - \frac{1}{k \pm g} (uv^2 \pm gm) \ldots (2)$$

This equation then will make known the load, in

tons gross, tender included, which corresponds to the velocity v.

It is necessary, however, here to observe that there are many ways of expressing the load of the engines in practice. It is most commonly expressed as we have done it, in tons gross, tender included, that is, including the weight of the tender of the engine. But, for certain inquiries, it is more convenient to express it, either in tons gross, tender *not* included; or in *effective* tons of goods, that is, exclusive both of the tender and of the waggons. To pass from the first of these expressions to the two others, we have evidently but to subtract the weight of the tender in the first case, and the weight of both tender and waggons in the second.

Thus, expressing by C the weight of the tender, the load of the engine, tender *not* included, will be

$$M - C;$$

and expressing by $\frac{1}{i}$ the average ratio of the weight of the goods carried on a waggon, to the total weight of the loaded waggon,

$$\frac{1}{i}(M - C)$$

will be the load of the engine in *effective* tons.

On railways of not more than about 5 feet of breadth of way, and for an engine weighing from 8 to 12 tons, the average weight of the tender may be valued at 6 tons, and the effective load of the wag-

gons is commonly $\frac{2}{3}$ of their total weight. We have then for the different expressions of the load,

M, load in tons gross, tender included;
M—6, load in tons gross, tender not included;
$\frac{2}{3}$M—4, load in effective tons.

It must be observed that the formula which we have just obtained, contains in its second member the term uv^2, in which u depends on the number of carriages in the train, as has been seen, Chapter IV. The precise value of this term could not then be determined till after the load of the engine be known, which is the quæsitum of the problem; but recourse will be had to approximations, as in the preceding research: that is to say, the second member of the formula must be calculated, exclusively of the term in which the quantity u figures, and calling B the result of that calculation, we have

$$M = B - \frac{uv^2}{k \pm g}.$$

Then making a first valuation of the quantity u, and substituting it in the equation, we shall conclude a corresponding value of the load M. If that load be such as to require for u the value supposed, or very nearly so, it is the load sought, and the problem is solved. But if the load thus found show that the value supposed for u was erroneous, it must be used to make a new valuation of u more exact than the first: this will consequently lead to a new determination of M, which will likewise be more approx-

imate than the former; and were it necessary, a third approximation might be made. But in general two trials will suffice; be it as it may, the equation is so simple, that these essays will be made rapidly and without the least difficulty.

Examining the formula which we have obtained above for the load of the engine, it will be remarked that taking the cases wherein g is preceded by the sign *minus*, and making $k-g=o$, that is, supposing the motion to take place in descending an inclined plane on which the friction of the waggons is counterbalanced by their gravity, the formula seems to give, for the suitable solution of the problem,

$$M=\frac{1}{o}.$$

But this apparent result depends only on the circumstance that uv^2 is not developed, and that it is really a function of M. In effect, we have seen, Chapter IV., that the value of uv^2, which represents the resistance of the air, depends not only on the transverse section of the train, but likewise on the number of carriages which compose it, and consequently on the weight of the train. The result obtained above is then caused simply by the coefficient of the only term in which the quantity M is expressed, becoming null by the supposition of $k-g=o$; but it will presently appear that referring to the value of the term uv^2, the weight of the load M is no less limited and easy to determine.

In effect, if we resume the equation (2) and write it under the form

$$(k \pm g)M \pm gm + uv^2 = \frac{1}{1+\delta}\left[\frac{1}{5280}\cdot\frac{l}{l+c}\cdot\frac{S}{qv} - F - \frac{d^2 l}{D}\left(\frac{n}{q} + p + p'v\right)\right],$$

it will be recognised that the first member expresses the total resistance opposed by the train, namely, the gravity and friction of the waggons, the gravity of the engine, and finally, the resistance of the air against the train. But if, in this equation, we make $k-g=o$, it becomes

$$uv^2 - gm = \frac{1}{1+\delta}\left[\frac{1}{5280}\cdot\frac{l}{l+c}\cdot\frac{S}{qv} - F - \frac{d^2 l}{D}\left(\frac{n}{q} + p + p'v\right)\right];$$

that is to say, in this case, the resistance of the train reduces itself to that of the air diminished by the gravity of the engine. The quantity M then ostensibly disappears from the equation, but it nevertheless remains represented by the term uv^2, and by this term will be obtained the solution sought; for resolving the equation with reference to uv^2, we derive

$$uv^2 = \frac{1}{1+\delta}\left[\frac{1}{5280}\cdot\frac{l}{l+c}\cdot\frac{S}{qv} - F - \frac{d^2 l}{D}\left(\frac{n}{q} + p + p'v\right)\right] + gm.$$

Now the velocity of the motion is given. Therefore this equation will make known the quantity u, and, as a consequence, the *effective* surface offered to the shock of the air by the train in motion. But we have seen, Chapter IV., that, for a railway of 5 feet of width of way, that effective surface is equal to 70 square feet, plus as many times 10 feet as there are waggons. We may then, from the know-

ledge of u, deduce the number of carriages, and as we know besides the average weight of a carriage, we shall conclude, in fine, the definitive weight of the train, which will be limited and not infinite.

There is yet another case in which the formula just obtained for the load of the engine, seems to give the result of $M=\frac{1}{o}$: it is the case wherein it is supposed $v=o$. The consequence then would be that the load corresponding to a velocity null would be infinite. But observing the formula more attentively, we recognise that it by no means gives this result. It will be recollected, in effect, that the quantity S represents the *effective* vaporization of the engine, or the volume of water which really passes, in the state of steam, into the cylinders. Now if we suppose the velocity null, it is evident that no steam at all can pass into the cylinders, since that steam could not traverse them without driving the pistons, and consequently creating some velocity in the engine. The supposition therefore of $v=o$ necessarily carries with it that of $S=o$, and consequently the value of M then presents itself under the form

$$M=\frac{o}{o}.$$

Thus, in this case, the formula reduces itself to the indeterminate form; but it must be observed that the formulæ under consideration are intended to

make known the effects of the engine, only when it has attained uniform and permanent motion. Now it will presently be seen, in seeking the velocity of maximum useful effect, that for a given vaporization S, the uniform velocity of the engine can never be less than

$$v' = \frac{1}{5280} \cdot \frac{S}{d^2} \cdot \frac{D}{l+c} \cdot \frac{1}{n+qP},$$

because this velocity is that which corresponds to the passage of the steam into the cylinders in its state of greatest density or highest pressure, and that at any other less density, the steam would necessarily occupy a greater volume, and consequently could not traverse the cylinders without producing a greater velocity in the engine. All supposition of a smaller velocity than the above is therefore inadmissible in the problem, as being incompatible with the state of permanence and uniformity of motion for which alone the effects of the engines are calculated.

Sect. VI. *Of the different expressions of the useful effect of the engine.*

We have said that there are many modes of expressing the useful effect of the engines. We are about to consider each of them successively.

1st. The useful effect produced by an engine in a given time, is the product of the mass conveyed and the distance to which it is conveyed, in the

given time. Now, in the engines under consideration, the mass conveyed is represented by the quantity M, or by the number of tons drawn by the engine. The velocity v likewise expresses the distance traversed by the engine, or, in other words, the distance traversed by the load, during the unit of time. Hence the product Mv is no other than the useful effect produced by the engine during the unit of time.

To obtain the expression of this useful effect, it will consequently suffice, to draw from equation (2) the value of Mv, which will be done by multiplying both terms by v; and thus we shall have

$$\text{u. E.} = Mv = \frac{1}{(1+\delta)(k \pm g)} \left[\frac{1}{5280} \cdot \frac{1}{l+c} \cdot \frac{S}{q} - \frac{d^2 lv}{D} \left(\frac{n}{q} + p + p'v \right) - Fv \right] - \frac{v}{k \pm g} (uv^2 \pm gm) \ldots (3)$$

We have thus the solution of the problem; and it will be observed that this expression of the useful effect, for a given vaporization S, varies with the velocity of the engine, as may have been already remarked in the experiments which we have presented, Sect. II. Chapter XI.

In practice, the desired result may be attained more simply, by seeking first, from equation (2), the numerical value of the load M corresponding to the velocity v, then multiplying that load by the given velocity. For instance, we have already found, Sect. IV. Article I. of this chapter, that at the velocity of 19·67 miles per hour, and ascending a plane inclined $\frac{1}{500}$, an engine of the dimensions

before indicated, would draw a load of 50 tons. We are then to conclude that the useful effect which the engine will produce at that velocity and on that plane, will be 983 tons conveyed 1 mile per hour.

The solution which we have just given of the problem suits the case in which it is required to find the useful effect produced at a known velocity. But if, on the contrary, the load is given, and it be required to find the useful effect that the engine will produce with that load, then the velocity corresponding to the given load must first be sought, from equation (1) or (1 bis), and that velocity multiplied by the given load will be the corresponding useful effect.

We must here call to mind that the load M of the engine is measured in tons gross, tender included, and consequently the useful effect $M v$ is the useful effect of the engine in tons gross drawn 1 mile, tender included. But as we have seen that representing by C the weight of the tender, and by $\frac{1}{i}$ the ratio of the effective load of a waggon to its total weight, the load of the engine may be expressed in three ways, namely:

M, ... load in tons gross, tender included;

$M-C$, . . load in tons gross, tender not included;

$\frac{1}{i}(M-C)$, load in effective tons;

it is plain that the useful effect of the engine, in

tons drawn 1 mile, may be likewise expressed in three ways, which are:

$M v$, ... useful effect, in tons gross drawn 1 mile, tender included;

$M v - C v$, . useful effect, in tons gross drawn 1 mile, tender not included;

$\frac{1}{i}(M - C) v$, useful effect, in effective tons drawn 1 mile.

We have already said that on railroads of but about 5 feet of width of way, the average weight of the tender may be valued at 6 tons, and the effective load at $\frac{2}{3}$ of the gross load; we have therefore $C = 6$ and $\frac{1}{i} = \frac{2}{3}$. Thus in the example above mentioned, the useful effect of the engine, in tons gross drawn 1 mile per hour, may be expressed in the three following manners:

983 tons gross drawn 1 mile, tender included;
865 tons gross drawn 1 mile, tender not included;
577 effective tons drawn 1 mile.

The three modes which we have just indicated to express the load, and consequently the useful effect of the engines, are all in use; the choice among them depends merely on the object in view at the time. As, however, they may easily be concluded one from another, and as the most simple consists in taking the load, in tons gross, tender included, this will be the method which we shall employ. The only exception which we shall make to this

rule, will be in the inquiry as to the expenditure of coke and water per ton per mile, in which, to conform to the usual practice, we shall refer the expenditure to the load, in tons gross, tender *not* included. But, in every other case, we will suppose the load and the useful effect measured in tons gross, tender included, and it will always be this that we intend to signify by the *useful effect* of the engine, when we do not specify to the contrary.

2nd. The expression furnished by formula (3), or the equivalent mode of calculation which we have pointed out, makes known the useful effect of the engine, in tons conveyed 1 mile in an hour. But, as we have before said, the useful effect of an engine may be expressed under several forms. It will be proper then to seek those different expressions.

A very simple mode of making known the effect of an engine, consists in representing it by the number of horses that would be required to produce the same effect, not at the same velocity, but in the same time. With this view, the expression *one horse-power* has been made to designate an effect of 33000 ℔s. raised one foot per minute. This measure has arisen from the observation having been made that a vigorous horse going at a walking pace, or about 220 feet per minute, which is the most advantageous speed, may, permanently and without fatigue, exert an effort of 150 ℔s., or, in other words, raise a weight of 150 ℔s. suspended at the end of a cord which passes over a pulley.

It is plain that, in this labour, the useful effect produced is 33000 lbs. raised 1 foot per minute, and it is for this reason that this effect is designated by the name of *horse-power;* but it would be much more exact, as we have remarked in another work, to call it *horse-effect*, since it is an effect and not a force. It would then be said that an engine is of so many horse-effect, instead of saying that it is of so many horse-power. The expression would be more correct; but it suffices to have a clear understanding as to the value of the terms.

To apply the measure which has just been given, to the effect of locomotive engines, it suffices to observe that the traction of one ton gross, on a railway, offers a resistance of 6 lbs., that a mile represents a length of 5280 feet, and that an hour contains 60 minutes. Any useful effect then whatever, expressed in pounds raised 1 foot per minute, may be transformed into tons gross drawn 1 mile per hour, by multiplying by the factor,

$$\frac{60}{6 \times 5280} = \frac{1}{528};$$

and consequently the force or the effect of one horse, expressed in this manner, is represented by

$$\frac{33000}{528} = 62{\cdot}5 \text{ tons gross drawn 1 mile per hour.}$$

As soon as the effect of one horse has thus been referred to the usual measures on railroads, nothing

is more easy than to find the effect of a locomotive engine, in horse-power. For that purpose, it evidently suffices to divide the useful effect $M v$ already obtained, by the new unity adopted. We have thus the number of those unities which represent the effect $M v$, and consequently the useful effect of the engine expressed in horses. This effect then will be

$$\text{u. E. in HP.} = \frac{M v}{62 \cdot 5}.$$

It will be remarked that the product $M v$, or the useful effect of the engine, varies with the velocity of the motion; and it will be seen further on that this product is by so much greater as the velocity is less.

It is the same with effects produced by horses; for we know that the useful effect due to their labour decreases rapidly as their speed increases, and that it is only at the most advantageous speed that this effect can be valued at 33000 ℔s. raised 1 foot per minute. When therefore the useful effect of an engine is expressed, under whatever form, it will always be necessary, in order to be exact, to relate at the same time the velocity at which that effect is produced, or, which amounts to the same, the load with which it is produced; and if this measure is used in an absolute manner, as it is with respect to the horse, it should then be understood that the effect indicated is that of the

most advantageous labour of the engine. As we shall presently obtain the measure of the maximum useful effect a given locomotive engine can produce, we may then also express that useful effect in horse-power. It will be this valuation then, that is to say, the greatest effect the engine can produce, working at the minimum or most advantageous velocity, that we shall always intend, when we say in an *absolute* manner that an engine is of the effect or of the force of so many horses; but, in every other case, in indicating the effect of an engine in horse-power, we shall always express at what velocity or with what load such effect is produced.

3rd. In the two preceding questions we have expressed the total effect the engine can produce in the unit of time, without regard to its consumption of water and fuel. We are now going, on the contrary, to express that effect with reference to the expense which is necessary to produce it.

The useful effect obtained in equation (3), is that which is produced by the effective vaporization S of the engine, or, in other words, by the total vaporization S′ of the boiler; and as we have seen that this vaporization S or S′ is that which takes place in the unit of time, the corresponding useful effect is also the useful effect produced during the unit of time. But if it be supposed that to effect this vaporization the engine requires the consumption of N ℔s. of fuel, it is clear that then N ℔s. of fuel will be sufficient to draw 1 mile a number of tons expressed

by $M v$. Therefore, by a simple proportion, the quantity of fuel necessary to draw a ton 1 mile will be

$$\frac{N}{M v}.$$

It will, however, be observed that the quantity M indicates the load of the engine, *tender included*. The number $M v$ represents then the number of tons, tender included, the conveyance of which 1 mile has been performed by the weight N of coke; and consequently the result which we have just obtained expresses the weight of coke expended per ton gross per mile, tender included, that is, taking into the calculation the weight of the tender.

But if it be desired, as is customary on railways, to know the expenditure of fuel which will be necessary for a given work, *tender not included*, recourse must then be had to the expression of the useful effect of the engine, in tons 1 mile, tender not included. We have seen that expressing by C the weight of the tender, the useful effect of the engine expressed in tons gross conveyed 1 mile, tender not included, is

$$(M - C) v = M v - C v.$$

Since, therefore, this effect is produced by the consumption of N lbs. of coke, the quantity of coke, in pounds, necessary per ton gross per mile, tender not included, will be expressed by

$$\text{Q. co. pr. t. pr. m.} = \frac{\mathrm{N}}{\mathrm{M}v - \mathrm{C}v}.$$

To apply this formula it will suffice to know the number of pounds of coke consumed in the fire-box, to operate in the boiler the total vaporization S′; which the experiments developed Chapter XI. have enabled us to do. It will therefore be easy to solve the problem proposed.

It is yet to be observed that the quantity of coke necessary per ton per mile, must vary in the same engine, with the velocity of the motion; because the product M v is by so much the smaller as the velocity is greater, whereas we have shown, in treating of the fuel, that the quantity N, or the expenditure of coke necessary to operate a determined vaporization, varies but in an insensible degree with the velocity. This result as to the variation of fuel per ton per mile has already been noticed, Chapter XI.

4th. From what we have said above, the *effective* vaporization S has sufficed to draw 1 mile a number of tons gross expressed by M v, tender included, or by (M—C) v, tender not included. The quantity therefore of water *effectively* vaporized, which has performed the conveyance of a ton 1 mile, tender not included, is expressed by

$$\frac{\mathrm{S}}{\mathrm{M}v - \mathrm{C}v}.$$

But as it is more convenient to refer the useful

effect to the *total* or gross vaporization of the boiler, and as we have expressed this by S′, we shall have for the quantity of *total* vaporization, necessary to draw 1 ton gross 1 mile, tender not included,

$$\text{Q. wa. pr. t. pr. m.} = \frac{S'}{M\,v - C\,v}.$$

5th. To obtain the useful effect produced per pound of fuel, it is to be observed that, since the useful effect M v has been produced by the consumption of N ℔s. of coke, the useful effect produced by each pound of coke must be the Nth part of the above effect. Thus this useful effect, expressed in tons gross drawn 1 mile, tender included, will be

$$\text{u. E. 1℔. co.} = \frac{M\,v}{N}.$$

6th. Similarly, to obtain the useful effect produced per cubic foot of water vaporized, it will be observed that, since the useful effect M v is that which is due to the total vaporization S′ of the boiler, that is to say, to the number S′ of cubic feet of water vaporized, the useful effect produced by the vaporization of 1 cubic foot of water will be had by dividing the useful effect M v by the number of unities that there are in S′.

Thus the useful effect produced per cubic foot of *total* or gross vaporization, and expressed in tons gross drawn 1 mile, tender included, will be expressed by

$$\text{u. E. 1 ft. wa.} = \frac{M\,v}{S'}.$$

7th. We have obtained, in the 5th problem, the useful effect produced per pound of fuel. It will therefore be easy to deduce the number of pounds of fuel necessary to produce the effect of one horse. A simple proportion will evidently suffice, and the quantity of fuel, in pounds, which produces the effect of one horse, will be expressed by

$$\text{Q. co. pr. HP.} = \frac{62{\cdot}5\ N}{M\,v}.$$

8th. We find in the same manner, by a simple proportion, the quantity, in cubic feet, of total water vaporized, which produces the effect of one horse, namely:

$$\text{Q. wa. pr. HP.} = \frac{62{\cdot}5\ S'}{M\,v}.$$

9th. The effect, in horse-power, produced by the consumption of 1 ℔. of fuel, will evidently be

$$\text{u. E. in HP. of 1 ℔. co.} = \frac{M\,v}{62{\cdot}5\ N}.$$

And, 10th, finally, the effect, in horse-power, produced per cubic foot of *total* water vaporized, will be expressed by

$$\text{u. E. in HP. of 1 ft. wa.} = \frac{M\,v}{62{\cdot}5\ S'}.$$

ARTICLE II.

OF THE MAXIMUM USEFUL EFFECT OF THE ENGINE.

SECT. I. *Of the velocity of maximum useful effect.*

We have hitherto determined the effects of the engines in a manner perfectly general, that is to say, taking the data of the problem without restricting them to any condition, except only that of being contained within the limits of the power of the engine. But an important question now presents itself. It is proposed, among all the different velocities that can be imagined for the engine, and each necessarily implying a certain corresponding load, to determine that which will produce the greatest useful effect. This problem is of great utility, since it shows in what case the engine will work in the most advantageous manner possible.

To solve this question, we must recur to the general expression of the useful effect produced by the engine, and seek what value of v will make it a *maximum*. This general expression is given by equation (3), namely:

$$\text{u. E.} = \frac{1}{(1+\delta)(k \pm g)} \left[\frac{1}{5280} \cdot \frac{l}{l+c} \cdot \frac{S}{q} - \frac{d^2 lv}{D} \left(\frac{n}{q} + p + p'v \right) - Fv \right] - \frac{v}{k \pm g} (uv^2 \pm gm).$$

Now, in observing this expression, we find that the velocity figures only in the negative terms; for

the factor $\frac{1}{k \pm g}$ could become negative, that is, change the apparent sign of the other terms, only in the case wherein the motion should be descending, and wherein at the same time we should have $g > k$. But in that case the train would be found placed on an inclined plane on which the waggons would roll of themselves; and consequently the useful effect Mv would no longer be the result of the force of the engine alone, but of that force *joined to the gravity*, which would become an *effective* motive force. To know therefore the conditions which render the useful effect of the engine a maximum, this case must be excluded; and thus we see that, in the expression brought forward, so long at least as it expresses only the effect proper to the engine, the velocity figures only in the negative terms. Hence, firstly, the greatest useful effect will take place at the lowest value of v.

But, from equation (1), the velocity v is expressed by

$$v = \frac{1}{5280} \cdot \frac{\mu S}{d^2} \cdot \frac{D}{l+c};$$

and it is clear that, for given dimensions and vaporization, this expression will be at its lowest value, when μ is the smallest possible. On the other hand, as the quantity μ represents the volume of the steam under the pressure R, it will evidently be at its least value when the pressure, or resistance R

against the piston, shall, on the contrary, be at its maximum. Hence, finally, the maximum useful effect of the engine takes place when the load is the greatest possible.

Now, it is plain that the resistance R can in no case exceed the pressure of the steam in the boiler, since the resistance would then be greater than the motive power, and the motion would thus become impossible. The maximum therefore of R, the minimum of v, and the maximum possible useful effect of the engine, will be given by the conditional equation

$$R = P.$$

Consequently, if we express by μ' the relative volume of the steam generated under the pressure P of the boiler, the velocity of maximum useful effect will be determined by putting μ' instead of μ in equation (1); that is to say, that velocity will be

$$v' = \frac{1}{5280} \cdot \frac{\mu' S}{d^2} \cdot \frac{D}{l+c}; \quad \ldots\ldots \quad (4)$$

or else, by putting for μ' its value,

$$\mu' = \frac{1}{n+qP},$$

that velocity may again be expressed by the formula

$$v' = \frac{1}{5280} \cdot \frac{S}{d^2} \cdot \frac{D}{l+c} \cdot \frac{1}{n+qP} \quad \ldots\ldots \quad (4 \text{ bis})$$

This equation then will make known the velocity corresponding to the maximum useful effect of the

engine, as soon as the quantities S, d, D, l and P shall be replaced by their value taken on the engine, and referred to homogeneous measures, as has been already said.

SECT. II. *Of the load corresponding to the maximum of useful effect.*

The load corresponding to the maximum of useful effect will be known by equation (2), on substituting in it instead of v, the value v' given above. But it will be obtained more simply, by deducing it directly from the condition

$$R = P,$$

which, substituting for R its value (Chapter IX.), becomes

$$(1+\delta)\left[(k \pm g)M \pm gm + uv^2\right]\frac{D}{d^2l} + \frac{DF}{d^2l} + p + p'v = P,$$

and which, when v is replaced by v', gives

$$M' = \frac{d^2l}{(1+\delta)(k \pm g)D}(P - p - p'v') - \frac{1}{k \pm g}\left(\frac{F}{1+\delta} \pm gm\right) - \frac{uv'^2}{k \pm g} \quad \ldots\ldots (5)$$

This formula, in which account must be taken of the variation of the term uv'^2, as has been said, Sect. v. of the preceding article of the present chapter, will make known the load that ought to be given to an engine to make it produce its maximum useful effect.

It is necessary here to remark, that as this load offers a resistance precisely equal to the pressure of

the steam in the boiler, and as we have seen that at the moment of starting of every engine, the power must necessarily exert an effort greater than the resistance, it would be impossible for the engine to set itself in motion with the load M′. If then we would make the engine work with this load, it is understood that the aid of another engine would be requisite to start it; or else the engine-man must for a few minutes close the safety-valve, to create in the boiler a sufficient excess of pressure, till the uniform motion be attained. Then the momentary excess of pressure may be withdrawn, and the engine will continue its motion without any external aid.

However, as on railways there continually occur little inequalities or accidental imperfections in the road, and as the engine ought to be capable of overcoming them, it is not to be expected that it can be made to perform an entire trip, working precisely at its maximum of useful effect, or with its maximum load. The preceding determination therefore is to be considered only as showing what the engine may perform on arriving with a velocity already acquired, at an inclined plane situated at a certain point of the line, or as indicating the point towards which our aim should tend as much as possible, in order to accomplish producing the maximum of useful effect, but without reckoning on obtaining it completely in practice.

We here neglect the little necessary difference

between the pressures in the cylinder and in the boiler, from the flowing of the steam from the one vessel to the other. It plainly tends somewhat to reduce the load of the engine, increasing in a corresponding manner the velocity of maximum useful effect.

Sect. III. *Of the measure of the maximum useful effect of the engine.*

The maximum useful effect of the engine will evidently be the product $M'v'$. Consequently, after having determined the velocity and the load, as has just been explained in the two preceding sections, it will suffice to multiply together the two quantities obtained. Thus we shall have

$$\text{m. u. E.} = M'v' \quad \ldots\ldots \quad (6)$$

The developed expression of the maximum useful effect might be obtained immediately, by performing the multiplication of the two values of v' and M' given by the equations (4 bis) and (5); but as it is much more simple to solve these two equations separately to derive v' and M' from them first, and then to multiply the two results together, as has just been pointed out, we will follow this mode of calculation.

To obtain the effect of the engine in horse-power, when working at its maximum of useful effect, and in like manner to obtain all the other modes of

expressing the effect produced, it evidently will suffice to substitute, in the general formulæ given on this head in the preceding article, for the product Mv, the product $M'v'$, which is suitable to the production of the maximum useful effect. We shall not dwell here on the divers expressions, since they would be but the reproduction of the formulæ already explained.

ARTICLE III.

PRACTICAL FORMULÆ FOR CALCULATING THE EFFECTS OF LOCOMOTIVE ENGINES, AND EXAMPLES OF THEIR APPLICATION.

We have hitherto presented the formulæ proper for calculating the effects of the engines, under a form completely algebraical, that is to say, leaving in them all the quantities represented by letters, without excepting the constant quantities whose values have been already determined in former chapters. But we now purpose to reduce these formulæ to their most simple practical form; in order to effect which, it will be proper to replace in them, as far as may be, the letters by the numerical values which they represent.

The letters which have a constant value in all cases and for all the engines are:

k, Friction of the waggons, which we have found equal to 6 lbs. per ton;

p, Atmospheric pressure, the value of which is 2118 lbs. per square foot;

n, Constant quantity relative to the volume of the steam, its value being ·0001421, when the pressure is measured in pounds per square foot;

q, Factor relative to the volume of the steam, equal to ·00000023 when the pressure is expressed in pounds per square foot;

c, Clearance of the cylinder, which may be taken generally at $\frac{1}{20}$ of the useful stroke of the piston, which gives $\frac{l}{l+c} = \frac{20}{21}$.

These values being constant for all engines, may be introduced permanently into the equations. Substituting them therefore for the respective letters, and effecting the calculation as much as possible, we obtain the following formulæ, which are quite prepared for practical applications.

In order to avoid recurring to another page of the work, we will first repeat here the signification of all the letters which subsist in these formulæ.

M, Load of the engine, in tons gross, tender included;

m, Weight of the engine, in tons;

C, Weight of the tender, in tons;

g, Gravity, in pounds, of 1 ton placed on the inclined plane to be traversed by the engine.

If the inclination of the plane be $\frac{1}{e}$, that gravity will have for its value, in pounds, $\frac{2240}{e}$; and if the plane be horizontal, the gravity will be equal to zero;

v, Velocity of the engine, expressed in miles per hour;

uv^2, Resistance of the air against the train, at the velocity v, a resistance expressed in pounds;

$p'v$, Pressure owing to the blast-pipe, expressed in pounds per square foot;

F, Friction of the engine, in pounds;

δ, Additional friction of the engine, measured as a fraction of the resistance, namely: ·14 for engines with uncoupled wheels, and ·22 for those with coupled wheels;

D, Diameter of the propelling wheels, in feet;

d, Diameter of the cylinder, in feet;

l, Stroke of the piston, in feet;

P, *Total* or absolute pressure of the steam in the boiler, in pounds per square foot;

S, Effective vaporization of the engine, in cubic feet of water per hour. It varies according to the engines, but may, on an average, be valued at ·75 of the total or gross vaporization, when there is no blowing of steam at the valves;

S′, Total vaporization of the boiler, at the velocity

of the motion, in cubic feet of water per hour;

N, Consumption of coke in the fire-box, in pounds per hour.

PRACTICAL FORMULÆ FOR CALCULATING THE EFFECTS OF LOCOMOTIVE ENGINES.

General case.

$$v = \frac{784\,S}{(1+\delta)\,[(6 \pm g)M \pm gm + uv^2] + F + \frac{d^2 l}{D}(2736 + p'v)} \ldots$$ Velocity of the engine, in miles per hour.

$$M = \frac{1}{(1+\delta)\,(6 \pm g)}\left[784\,\frac{S}{v} - \frac{d^2 l}{D}(2736 + p'v) - F\right] - \frac{1}{6 \pm g}(uv^2 \pm gm) \ldots\ldots$$ ...... Load of the engine, in tons gross, tender included.

u. E. .... $= M\,v$ .... Useful effect, in tons gross drawn 1 mile per hour, tender included.

u. E. in HP. ...... $= \frac{M\,v}{62{\cdot}5}$ .... Useful effect, in horse-power.

Q. co. pr. t. pr. m... $= \frac{N}{M\,v - C\,v}$ .... Quantity of coke in pounds, per ton gross drawn 1 mile, tender *not* included.

Q. wa. pr. t. pr. m... $= \frac{S'}{M\,v - C\,v}$ .... Quantity of water, in cubic feet, per ton gross drawn 1 mile, tender *not* included.

u. E. 1 lb. co....... $= \frac{M\,v}{N}$ .... Useful effect produced per pound of coke, in tons gross drawn 1 mile, tender included.

u. E. 1 ft. wa. .... $= \frac{M v}{S'}$ .... Useful effect produced per cubic foot of total vaporization, in tons gross drawn 1 mile, tender included.

Q. co. fr. 1 HP..... $= \frac{62 \cdot 5 \text{ N}}{M v}$ .... Quantity of coke in pounds, which produces the effect of 1 horse.

Q. wa. fr. 1 HP..... $= \frac{62 \cdot 5 \text{ S}'}{M v}$ .... Quantity of water, in cubic feet, which produces the effect of 1 horse.

u. E. 1 lb. co. in HP. $= \frac{M v}{62 \cdot 5 \text{ N}}$ .... Useful effect, in horse-power, produced per pound of coke.

u. E. 1 ft. wa. in HP. $= \frac{M v}{62 \cdot 5 \text{ S}'}$ .... Useful effect, in horse-power, produced per cubic foot of *total* vaporization.

Case of maximum useful effect.

$v' = \frac{1 \cdot 804}{1 \cdot 421 + \cdot 0023 \text{ P}} \cdot \frac{D}{l} \cdot \frac{S}{d^2}$ .... Velocity of maximum useful effect, in miles per hour.

$\text{M}' = \frac{d^2 l}{(1+\delta)(6 \pm g) \text{D}} (\text{P} - 2118 - p'v') - \frac{1}{6 \pm g} \left(\frac{\text{F}}{1+\delta} + uv'^2 \pm gm \right)$ .... Maximum load of the engine, in tons gross, tender included.

m. u. E. $= \text{M}'v'$. .... Maximum useful effect, in tons gross drawn 1 mile per hour, tender included.

We do not give the divers modes of expressing the maximum of useful effect in horse-power, &c., because those formulæ are the same as in the general case, on merely replacing M and v by M′ and v'.

That there may be no misunderstanding as to the manner of expressing the divers quantities contained in the formulæ, nor on the manner of performing the calculation, we will here give an example or two with some detail.

Suppose then a locomotive of 65 cubic feet of total vaporization, at the velocity of 20 miles per hour; with cylinders 11 inches or ·917 foot in diameter, stroke of the piston 16 inches or 1·33 foot, wheels 5 feet in diameter, not coupled, friction 103 lbs., weight 8 tons, blast-pipe 2·33 inches in diameter, *total* or absolute pressure in the boiler 65 lbs. per square inch, and consumption of coke per hour 598 lbs. Suppose this engine employed on a level railway, of about 5 feet of width of way, and let it be required to know what velocity it will attain with a train of 10 waggons weighing 56 tons, tender included, which is the same as 50 tons without tender.

1st. As the motion takes place on a horizontal plane, we have $g = 0$; and since the wheels of the engine are not coupled, we have $\delta = \cdot 14 = \frac{1}{7}$. Moreover, from the ratio which we have found between the total and the effective vaporization

of the engine, the value of the latter, at 20 miles per hour, is

$S = \cdot 75 \times 65 = 48 \cdot 75$ cubic feet of water per hour;

and in fine, from the proportions of the engine, we have

$$\frac{d^2 l}{D} = \overline{\cdot 917}^2 \times \frac{1 \cdot 33}{5} = \cdot 2237.$$

This done, to find what velocity the engine will acquire in drawing the train of 56 tons, we will first suppose that it may be, approximatively, 23 miles per hour, and we shall then have, for the pressure in the blast-pipe, 4 lbs. per square inch, or $p'v = 576$ lbs. per square foot. As the effective surface presented to the shock of the air, valued according to the mode explained Chapter IV., is $\Sigma = 70 + 10 \times 12 = 190$ square feet, the resistance of the air at the velocity of 23 miles per hour, will be $uv^2 = 270$.

Thus the value of v, taken without supposing that the vaporization changes with the velocity, will be

$$v = \frac{784 \times 48 \cdot 75}{1 \cdot 14\ (6 \times 56 + 270) + 103 + \cdot 2237\ (2736 + 576)} = 24 \cdot 88.$$

This first essay of calculation gives then 24·88 miles per hour, for the velocity of the engine, and we conclude from it that the two terms uv^2 and $p'v$ which we have calculated on the supposi-

tion of $v = 23$, have not been valued in a manner sufficiently exact, but that the true velocity is comprised between 24·88 and 23 miles.

Trial then might be made of $v = 24$, and this value would be found to satisfy the problem, when the variation which the vaporization undergoes with the velocity of the motion is neglected. Thus approximatively we might hold to this result; but if it be desired to calculate with greater accuracy, it will be proper to introduce the increase of vaporization due to the velocity.

For this purpose, as the increase of vaporization will have the effect of increasing the result of the calculation, we will try a number greater than 24, as $v = 25$, for instance. Supposing then this datum for the valuation of the variable quantities, we shall have

$$S = 51{\cdot}55,$$
$$p'v = 630,$$
$$uv^2 = 319;$$

and resolving the equation with these values we find

$$v = 25{\cdot}19.$$

Consequently, in fine, taking a mean between 25 and 25·19, we have, for the definitive velocity sought,

$$v = 25{\cdot}10 \text{ miles per hour.}$$

Such then will be the velocity which the engine will assume, when drawing on a level a train of 56 tons, tender included.

2nd. To continue this example of the application of the formulæ, let it be required to find what will be the velocity of the maximum useful effect of the engine.

In order to effect this, we will replace in the equation proper to that problem, the pressure P in the boiler by its value $P = 65 \times 144 = 9360$ lbs. per square foot; and supposing first that the vaporization of the engine will undergo no change notwithstanding the reduction of velocity, we obtain the result

$$v' = \frac{1{\cdot}804 \times 48{\cdot}75}{1{\cdot}421 + {\cdot}0023 \times 9360} \cdot \frac{1}{{\cdot}2237} = 17{\cdot}13.$$

This would then be the velocity sought, if the vaporization of the engine were invariable; but as the diminution of velocity will lower the vaporization, which is such as we have supposed it, only at the velocity of 20 miles per hour, we will try whether the velocity of 16 miles will suit the formula. Then the effective vaporization of the engine, reduced in the proportion of the fourth roots of the velocities, will become 46·10 cubic feet of water per hour, and the formula resolved according to this supposition, will give

$$v' = 16{\cdot}20 \text{ miles per hour.}$$

This is therefore the velocity suitable to the production of the maximum useful effect required.

3rd. In fine, to obtain the load corresponding to the maximum of useful effect, we recur to the proper equation, which is

$$M' = \frac{d^2 l}{D} \cdot \frac{1}{6(1+\delta)} (P - 2118 - p'v') - \frac{F}{6(1+\delta)} - \frac{uv'^2}{6};$$

and first calculating in this all the terms, except the last, we have as a result

$$208{\cdot}46.$$

It remains then to subtract from this number the value of $\frac{uv'^2}{6}$, to conclude from it definitively the required value of the load. As the value of the term

$$\frac{uv'^2}{6}$$

depends on the number of carriages in the train, which will itself be known only by the definitive solution of the problem, we will again in this place follow the method of approximations. Supposing the load to be of about 160 tons, the train will consist of 31 carriages besides the tender; thus the effective surface offered to the shock of the air, will be

$$\Sigma = 70 + 33 \times 10 = 400 \text{ square feet.}$$

Consequently the resistance of the air, at the velocity found, of 16·20 miles per hour, will be $uv'^2 = 282$ lbs., which gives

$$\frac{uv'^2}{6} = 47{\cdot}00;$$

substituting then this valuation in the formula, we obtain the result

$$M' = 208 \cdot 46 - 47 \cdot 00 = 161 \cdot 46.$$

Consequently the load of 161·5 tons, forming a train of 31 carriages, besides the tender, will be the maximum load required.

4th. In fine, if it be desired to know the maximum velocity the engine is capable of attaining, when followed by its tender only, and without drawing any train, the proceeding will be as in the first case; but supposing the load to be of 6 tons only, and taking account of the increase of vaporization, according to the velocity, the result will be

$$v = 35 \cdot 03 \text{ miles per hour.}$$

In this last case, the useful effect of the engine, *tender not included*, will be null.

From these detailed examples is seen how the calculation is to be performed in all the cases; but it must be remarked, that with the use of logarithms, these different trials present no sort of difficulty, and that those who have once got the habit of these researches, guess immediately and at a glance, what numbers they ought to employ in the approximations, so that the apparent length of the calculation entirely disappears.

Collecting the results which we have just obtained, calculating moreover the useful effect of the engine, and expressing it under the different forms already indicated, we form the following Table:

Effects of a locomotive of 65 *cubic feet of vaporization, with a load of* 56 *tons gross, on a level, tender included.*

M . . . . = 56 tons gross, tender included, (10 carriages and the tender);
v . . . . = 25·10 miles per hour;
u. E. . . . . . . = 1411 tons gross drawn 1 mile per hour, tender included;
u. E. in HP. . . = 23 horses;
Q. co. pr. t. pr. m. = ·47 lb. per ton gross per mile, tender *not* included;
Q. wa. pr. t. pr. m. = ·052 cubic foot per ton gross per mile, tender *not* included;
u. E. 1 lb. co. . . = 2·36 tons gross drawn 1 mile, tender included;
u. E. 1 ft. wa. . . = 21·70 tons gross drawn 1 mile, tender included;
Q. co. fr. 1 HP. . = 26·50 lbs.;
Q. wa. fr. 1 HP. . = 2·880 cubic feet;
u. E. 1 lb. co. in HP.= ·038 horse;
u. E. 1 ft. wa. in HP.= ·347 horse.

Maxima effects of the same engine.

M′ . . . . . . = 161·5 tons gross, tender included (31 carriages and tender);
v' . . . . = 16·20 miles per hour;
u. E. . . . . . . = 2616 tons gross drawn 1 mile per hour, tender included;
u. E. in HP. . . = 42 horses;
Q. co. pr. t. pr. m. = ·24 lb. per ton gross per mile, tender *not* included;
Q. wa. pr. t. pr. m. = ·026 cubic foot per ton gross per mile, tender *not* included;
u. E. 1 lb. co. . . = 4·38 tons gross drawn 1 mile, tender included;

u. E. 1 ft. wa. . . = 40·25 tons gross drawn 1 mile, tender included;
Q. co. fr. 1 HP. . = 14·29 lbs.
Q. wa. fr. 1 HP. . = 1·553 cubic foot;
u. E. 1 lb. co. in HP. = ·070 horse;
u. E. 1 ft. wa. in HP. = ·644 horse.

To give a second example of this calculation, we will suppose the railway to have 7 feet of width of way, like the *Great Western Railway*, and seek what will be the velocity of the engines of medium force, in use on that line, under the same circumstances as we have just examined relatively to a railway of about 5 feet of width of way.

We will suppose then a locomotive of 120 cubic feet of vaporization, at the velocity of 25 miles per hour, with the following proportions: cylinders 14 inches or 1·17 foot in diameter, stroke of the piston 16 inches or 1·33 foot, wheels 8 feet in diameter, not coupled, weight 18 tons, friction 270 lbs., blast-pipe 3·14 inches in diameter, total or absolute pressure in the boiler 80 lbs. per square inch, and consumption of coke in the same time 1050 lbs. or 8·75 lbs. per cubic foot of water vaporized. Moreover, by reason of the width of the way, we will take the surface of the largest waggon of the train at 100 square feet, the average surface of a waggon at 56 square feet, and the weight of the tender at 10 tons.

Seeking then by the same calculation as before, what effects this engine is capable of producing, first in drawing a train of 60 tons gross, tender included,

which makes 50 tons without the tender, and afterwards in drawing its maximum load, we obtain the following results:

Effects of a locomotive of 120 *cubic feet of vaporization, with a load of* 60 *tons gross, tender included.*

M . . . . = 60 tons gross, tender included (7 carriages and the tender);
v . . . . = 34·75 miles per hour;
u. E. . . . . . . = 2085 tons gross drawn 1 mile per hour, tender included;
u. E. in HP. . . = 33 horses;
Q. co. pr. t. pr. m. = ·60 lb. per ton gross per mile, tender *not* included;
Q. wa. pr. t. pr. m. = ·069 cubic foot per ton gross per mile, tender *not* included;
u. E. 1 lb. co. . . = 1·99 ton gross drawn 1 mile, tender included;
u. E. 1 ft. wa. . . = 17·38 tons gross drawn 1 mile, tender included:
Q. co. fr. 1 HP. . = 31·48 lbs.;
Q. wa. fr. 1 HP. . = 3·597 cubic feet;
u. E. 1 lb. co. in HP. = ·032 horse;
u. E. 1 ft. wa. in HP. = ·278 horse.

Maxima effects of the same engine.

M′ . . . . . . = 147 tons gross, tender included (20 carriages and the tender);
v' . . . . = 25·55 miles per hour;
u. E. . . . . . . = 3756 tons gross drawn 1 mile per hour, tender included;
u. E. in HP. . . = 60 horses;

Q. co. pr. t. pr. m.	=	·30 ℔. per ton gross per mile, tender *not* included;
Q. wa. pr. t. pr. m.	=	·034 cubic foot per ton gross per mile, tender *not* included;
u. E. 1 ℔. co. . .	=	3·58 tons gross drawn 1 mile, tender included;
u. E. 1 ft. wa. . .	=	31·30 tons gross drawn 1 mile, tender included;
Q. co. fr. 1 HP. .	=	17·47 ℔s.;
Q. wa. fr. 1 HP. .	=	1·997 cubic foot;
u. E. 1 ℔. co. in HP.	=	·057 horse;
u. E. 1 ft. wa. in HP.	=	·501 horse.

The velocity of the same engine, drawing its tender alone, would be 43·28 miles per hour; which would be the maximum of velocity that this engine could attain.

It is visible, in these examples, that the above formulæ present no difficulty, and that it is merely necessary to preserve in them the homogeneity of the measures employed.

ARTICLE IV.

EXPERIMENTS ON THE VELOCITY AND LOAD OF THE ENGINES.

That a precise idea may be formed of the degree of accuracy attainable by the formulæ which we have just given, and that besides, in case of need, calculations may be grounded on material facts, we will here give a series of experiments, which we under-

took with a view to know the velocities at which the engines draw different loads, in their ordinary and regular work.

These experiments were made on the Manchester and Liverpool Railway, of which this is the section, such as it results from a survey made in the month of August, 1833, by Mr. J. Dixon, then engineer to the Company. We give only that part of it which is traversed by the locomotives. There are besides, under the town of Liverpool, three tunnels, worked by stationary engines.

The railway beginning at the Liverpool station, and ending at that of Manchester, traverses the following distances and inclinations:

·53	mile,	level.	
5·23	—	descent	$\frac{1}{1094}$
1·47	—	ascent	$\frac{1}{96}$
1·87	—	level.	
1·39	—	descent	$\frac{1}{89}$
2·41	—	descent	$\frac{1}{2768}$
6·60	—	descent	$\frac{1}{849}$
5·62	—	ascent	$\frac{1}{1300}$
4·36	—	ascent	$\frac{1}{4287}$
29·48	miles.		

During the experiments in question, the velocities were carefully taken by noting, in minutes and seconds, the moment of passing by every quarter of a mile on the road. The quarter miles are marked by numbered posts. At the same moment the

pressure of the steam in the boiler and in the blast-pipe was also observed.

The weight of the waggons was taken exactly, in tons, hundred-weights, and pounds; but we express it, for greater convenience, in tons and decimals of a ton. The tenders of the engines were not weighed; they are quoted at their average weight during the trip; namely, 5·5 tons when water is taken on the road, and only 5 tons when that is not the case. The carriages containing passengers could not be weighed, because the regulations of the railway do not admit of that delay; but we have here inserted their average weight, as well as that of the private carriages and trucks.

The state of the weather is noted, because it is well known that a wind a-head, and, above all, a side wind, which presses the flange of the wheels against the rails, increases the resistance of the train; and the date of each experiment is given as a point of verification.

The following Table contains the results of these experiments. The first column gives the description of the engine and its load, the second indicates the inclination of the portion of road traversed by the train, the third and fourth show the *effective* pressure of the steam in the boiler and in the blast-pipe, such as they were observed at the moment of the experiment. In the fifth we have given the opening of the regulator at the time, as a fraction

of its total size; but it must be added that the engine Star, on which we had caused graduated divisions to be marked, was the only one which admitted of measuring the opening with precision. In the other engines, the handle of the regulator did not turn on a graduated circle, and therefore we could only set down the degree of the opening as it might be estimated by the eye. The sixth column of the Table contains the velocity of the engine, such as it was observed, and, in fine, the following column gives the result of our formula for the case considered.

To perform the calculation relative to each engine, we use the determinations developed Chap. X. Thus we attend to the variation of the vaporization with the velocity of the motion, according to what has been indicated. We take account of the habitual blowing of the safety-valves during the progress, for all the engines, except the Star, which was not liable to such loss; and it will be recollected that this loss amounts on an average to ·05 of the total vaporization of the boiler. In the experiments made on the inclined planes, we likewise deduce the considerable loss which then manifests itself at the valves of all the engines, and of which the valuation has been seen for every case. We take account too of the water carried away with the steam without being vaporized, or, according to the technical term, the *prime* water; and for these divers elements of calculation, we refer to the

details contained in Chapter X., without repeating here, for each engine, the determination which concerns it. Relatively to the absolute size of the regulator of the engines, we refer likewise to the chapter where that subject will be specially treated; in that place will be found, for each engine, the dimensions of the steam-ways, and consequently of the orifice of the regulator when it is entirely open. But as the greater or less opening of the regulator has no other action than that of producing directly the blowing of the valve, or indirectly the reduction of vaporization in the boiler, and as the use we make of the *effective* vaporization in our formulæ already comprehends those two effects, we merely indicate, in the fifth column, the opening of the regulator, by a fraction of its total size; which will suffice for the finding of its absolute size, should it appear necessary. Finally, all the engines worked with more or less *lead of the slide*, which is a particular disposition that we shall treat of in Chapter XVI.; but as we shall then find that this lead was very slight, and as its effects besides are already found comprised in the loss of water by *priming*, such as we have determined it, we will avoid complicating our calculations with this addition. We shall make an exception however in this respect for the engine Vesta, because, in that engine, the loss by priming had been determined for another lead of the slide than that at which it worked in the experiment which we are about

to relate. For this case then we shall take account of the lead of the slide as will be indicated Chap. XVI.

In making the comparison between the observed and the calculated velocities, attention must be paid to several circumstances.

1st. There is reason to believe that, when engines work at less pressure in the boiler, they are liable to less loss by priming. As, therefore, we have made use in this respect of the mean determination for each engine, it is in general to be expected that in the cases of low pressure, the calculated velocities will be found somewhat too small, and that, in the contrary case, they will be rather too great.

2d. The direction of the wind must necessarily have some influence on the velocity of the train.

3d. When the water contained in the tender is very hot, since its heat diminishes continually as the journey advances, it will most commonly happen that the engine will vaporize more water, and consequently assume a greater velocity at the beginning of the experiment than at the end of it.

4th. The differences arising from the three preceding circumstances, become easily compensated by the irregularities in the vaporization of the engine; and these are inevitable, as well from the greater or less attention of the engine-man, as on account of the sudden slackening which the vaporization is subject to, every time it becomes necessary to heap up the fire or to refill the boiler. Thus,

since the observed velocities result from the actual and variable vaporization of the boiler, whereas the calculated velocities are determined from the mean vaporization of the engine, supposed to be uniform throughout the trip, there must necessarily occur, from time to time, considerable differences between the calculation and the observation; but it will readily be perceived that these differences depend on the irregularities of the vaporization, on observing that, in the same trip, the engine often assumes its greatest velocity at the moment when the gravity opposes the greatest resistance, or that two portions of the line, on which the gravity is sensibly the same, are traversed with velocities very different. However, were the experiment sufficiently prolonged, all these momentary irregularities would disappear almost entirely.

Experiments on the velocity and the load of locomotive engines.

Date of the experiment, and designation of the engine and its load.	Inclination of the road.	Observed effective pressure in the boiler.	Observed effective pressure in the blast-pipe.	Opening of the regulator, in a fraction of its total size.	Observed velocity, in miles per hour.	Calculated velocity, in miles per hour.	Observations.
		lbs. per sq. inch.	lbs. per sq. inch.		miles.	miles.	
STAR. Cylinder . . 14 in. Stroke . . . 12 in. Wheel . . . 5 ft. Weight . . 11·20 t. Fire-box . . 49·71 sq. ft. Tubes . . . 279·18 sq. ft. Friction . . 176 lbs.							
STAR, Aug. 10, 1836, from Liver. to Man., with 12 wag. and tender, 43·65 tons. Gross vaporiz. per hour, 65·49 cubic feet, at the mean velocity of 20·78 miles per hour. Diameter of blast-pipe, 2·36 in.	d. $\frac{1}{1094}$	30·0	4·8	1	23·64	22·12	Weather fair and calm. Water in the tender hot.
	0	27·1	2·4	1	20·00	21·88	
	d. $\frac{1}{849}$	18·0	1·8	1	25·00	24·10	
	a. $\frac{1}{1800}$	22·6	2·9	1	20·69	20·14	
	a. $\frac{1}{4237}$	20·2	2·2	1	20·77	21·22	
STAR, Aug. 13, 1836, from Man. to Liver., with 9 wag. and tender, 48·48 tons. Gross vaporiz. per hour, 62·83 cubic feet, at the mean velocity of 18·79 miles per hour. Diameter of blast-pipe, 1·78 in.	d. $\frac{1}{4237}$	27·7	5·4	1	21·82	20·82	Weather fair and calm. Water in the tender hot.
	d. $\frac{1}{1800}$	26·0	5·0	1	23·53	21·89	
	a. $\frac{1}{849}$	28·0	4·2	1	18·75	18·83	
	a. $\frac{1}{2762}$	23·8	3·4	1	19·20	20·23	
	0	26·4	4·9	1	20·00	19·66	
	a. $\frac{1}{1094}$	30·0	6·0	1	20·00	18·65	
STAR, Aug. 11, 1836, from Liver. to Man., with 12 wag. and tender, 59·84 tons. Gross vaporiz. per hour, 61·05 cubic feet, at the mean velocity of 18·32 miles per hour. Diameter of blast-pipe, 2·82 in.	d. $\frac{1}{1094}$	27·0	"	·5	24·62	22·00	Weather fair and calm. Water in the tender tepid.
	0	20·5	"	·5	16·67	19·97	
	d. $\frac{1}{2762}$	22·1	"	·5	20·87	20·85	
	d. $\frac{1}{849}$	32·7	"	·5	22·50	22·27	
	a. $\frac{1}{1800}$	31·0	"	·5	20·00	18·77	
	a. $\frac{1}{4237}$	24·3	"	·5	18·00	19·74	
STAR, Aug. 11, 1836, from Man. to Liver., with 9 waggons loaded, 6 waggons empty, and tender, 61·24 tons. Gross vaporiz. per hour, 65·50 cubic feet, at the mean velocity of 17·46 miles per hour. Diameter of blast-pipe, 1·26 in.	d. $\frac{1}{4237}$	"	"	·5	15·00	17·48	Weather fair and calm. Water in the tender cold.
	d. $\frac{1}{1800}$	"	"	·5	21·43	18·91	
	a. $\frac{1}{849}$	"	"	·5	16·79	15·97	
	a. $\frac{1}{2762}$	"	"	·5	18·75	17·00	

Date of the experiment, and designation of the engine and its load.	Inclination of the road.	Observed effective pressure in the boiler.	Observed effective pressure in the blast-pipe.	Opening of the regulator, in a fraction of its total size.	Observed velocity, in miles per hour.	Calculated velocity, in miles per hour.	Observations.
		lbs. per sq. inch.	lbs. per sq. inch.		miles.	miles.	
Star, Aug. 9, 1836, from Man. to Liver., with 3 wag. loaded, 32 wag. empty, and tender, 75·05 tons.	d. $\frac{1}{4287}$	41·6	4·8	1	16·96	19·03	Weather fair and calm.
	d. $\frac{1}{1800}$	42·5	5·1	1	17·50	19·92	Water in the tender very hot.
Gross vaporiz. per hour, 68·79 cubic feet, at the mean velocity of 14·45 miles per hour.	a. $\frac{1}{849}$	45·2	4·4	1	14·53	16·47	
	a. $\frac{1}{27682}$	48·6	5·8	1	16·67	17·46	
	0	44·3	5·3	1	16·39	18·30	
	a. $\frac{1}{1094}$	48·1	6·2	1	17·73	16·43	
Diameter of blast-pipe, 2 in.							
With 38·58 tons	a. $\frac{1}{89}$	49·6	2·8	1	9·11	10·27	
With 41·97 tons	a. $\frac{1}{89}$	50·6	1·8	1	7·28	10·11	
Star, Aug. 9, 1836, from Liver. to Man., with 20 wag. and tender, 96·30 tons.	d. $\frac{1}{1094}$	35·1	3·0	1	22·85	19·00	Weather fair and calm.
	0	42·3	2·4	1	20·00	17·00	Water in the tender hot.
Gross vaporiz. per hour, 60·64 cubic feet, at the mean velocity of 17·35 miles per hour.	d. $\frac{1}{27682}$	36·0	2·3	1	20·00	17·90	
	d. $\frac{1}{849}$	30·0	1·8	1	21·82	20·10	
	a. $\frac{1}{1800}$	40·0	2·3	1	17·56	15·58	
	a. $\frac{1}{4287}$	31·5	2·0	1	19·25	16·75	
Diameter of blast-pipe, 2·82 in.							
Star, Aug. 13, 1836, from Liver. to Man., with 22 wag. and tender, 109·68 tons.	d. $\frac{1}{1094}$	23·6	1·0	1	19·57	18·00	Weather fair and calm.
	0	38·8	2·4	1	13·33	14·38	Water in the tender cold.
Gross vaporiz. per hour, 54·20 cubic feet, at the mean velocity of 13·85 miles per hour.	d. $\frac{1}{27682}$	42·0	3·8	1	17·14	15·17	
	d. $\frac{1}{849}$	30·7	2·1	1	15·00	18·09	
	a. $\frac{1}{1800}$	37·5	1·6	1	12·63	13·60	
	a. $\frac{1}{4287}$	33·0	1·2	1	12·47	14·84	
Diameter of blast-pipe, 2 in.							
Star, Aug. 9, 1836, from Liver. to Man., with 23 wag. and tender, 120·27 tons.	d. $\frac{1}{1094}$	32·3	4·3	1	16·95	19·71	Weather fair and calm.
	0	48·0	5·0	1	15·00	16·87	Water in the tender almost cold.
Gross vaporiz. per hour, 67·71 cubic feet, at the mean velocity of 15·13 miles per hour.	d. $\frac{1}{27682}$	26·0	3·0	1	15·00	18·63	
	d. $\frac{1}{849}$	39·8	5·6	1	17·21	19·45	
	a. $\frac{1}{1800}$	41·2	4·4	1	15·24	15·03	
	a. $\frac{1}{4287}$	45·0	4·9	1	16·55	16·08	
Diameter of blast-pipe, 2 in.							

Date of the experiment, and designation of the engine and its load.	Inclination of the road.	Observed effective pressure in the boiler.	Observed effective pressure in the blast-pipe.	Opening of the regulator, in a fraction of its total size.	Observed velocity, in miles per hour.	Calculated velocity, in miles per hour.	Observations.
		lbs. per sq. inch.	lbs. per sq. inch.		miles.	miles.	
VESTA. Cylinder .. 11·125 in. Stroke ... 16 in. Wheel ... 5 ft. Weight ... 8·71 t. Fire-box .. 46·00 sq. ft. Tubes ... 215·66 sq. ft. Blast-pipe .. 2·50 in. Friction .. 181 lbs.							
VESTA, Aug. 1, 1834, from Man. to Liver., with 5 waggons loaded, 5 empty, and tender, 33·15 tons. Gross vaporiz. per hour, 65·00 cubic feet, at the mean velocity of 27·33 miles per hour.	d. $\frac{1}{4287}$ d. $\frac{1}{1800}$ a. $\frac{1}{849}$ a. $\frac{1}{89}$ o a. $\frac{1}{1094}$	50 50 50 55 50 50	,, ,, ,, ,, ,, ,,	1 1 1 1 1 1	30·00 34·74 28·93 14·11 29·00 28·80	30·60 31·07 29·09 15·50 30·18 29·11	Weather fair. A moderate wind in favour of the motion. Water in the tender very hot.
FIREFLY. Cylinder . 11 in. Stroke .. 18 in. Wheel .. 5 ft. Weight .. 8·74 t. Fire-box . 43·91 sq. ft. Tubes . 317·71 sq. ft. Blast-pipe 2·25 in. Friction 123 lbs.							
FIREFLY, July 26, 1834, from Liver. to Man., with 8 first-class coaches, and tender, 41·40 tons. Gross vaporiz. per hour, 64·10 cubic feet, at the mean velocity of 17·70 miles per hour.	o d. $\frac{1}{849}$ a. $\frac{1}{1800}$ a. $\frac{1}{4287}$	50 45 45 35	,, ,, ,, ,,	1 1 1 1	24·00 25·45 21·29 21·33	25·09 27·08 23·96 24·48	Weather fair. Water in the tender almost cold. The engine in a bad state, losing water by the tubes of the boiler.
FIREFLY, July 26, 1834, from Man. to Liver., with 8 first-class coaches, and tender, 41·40 tons. Gross vaporiz. per hour, 77·31 cubic feet, at the mean velocity of 21·33 miles per hour.	d. $\frac{1}{4287}$ d. $\frac{1}{1800}$ a. $\frac{1}{849}$ o a. $\frac{1}{1094}$	45 50·33 50·5 50·33 50	,, ,, ,, ,, ,,	·5 ·5 ·5 ·5 ·5	23·68 24·44 23·44 25·71 24·82	27·93 28·56 25·40 26·59 25·70	Weather rainy. A rather strong wind against the direction of the motion. Water in the tender tepid. The engine in a bad state, losing water by the tubes of the boiler.

Date of the experiment, and designation of the engine and its load.	Inclination of the road.	Observed effective pressure in the boiler.	Observed effective pressure in the blast-pipe.	Opening of the regulator, in a fraction of its total size.	Observed velocity, in miles per hour.	Calculated velocity, in miles per hour.	Observations.
		lbs. per sq. inch.	lbs. per sq. inch.		miles.	miles.	
FURY. Cylinder . . 11 in. Stroke . . . 16 in. Wheel . . . 5 ft. Weight . . . 8·20 t. Fire-box . . 32·87 sq. ft. Tubes . . . 267·84 sq. ft. Blast-pipe . 2·156 in. Friction . . 96 lbs.							
FURY, July 24, 1834, from Man. to Liver., with 10 wag. and tender, 48·80 tons. Gross vaporiz. per hour, 57·46 cubic feet, at the mean velocity of 18·63 miles per hour.	d. $\frac{1}{4287}$ d. $\frac{1}{1800}$ a. $\frac{1}{849}$ a. $\frac{1}{89}$ 0 a. $\frac{1}{1094}$	55 55 55 67 55 55	" " " " " "	·75 ·75 ·75 1 ·75 ·75	21·43 22·00 18·62 15·00 17·50 18·46	20·73 21·72 18·57 8·00 20·10 18·80	Weather fair. A rather strong side wind at intervals. Water in the tender cold.
FURY, July 24, 1834, from Liver. to Man., with 10 wag. and tender, 56·16 tons. Gross vaporiz. per hour, 54·45 cubic feet, at the mean velocity of 19·67 miles per hour.	d. $\frac{1}{1094}$ a. $\frac{1}{96}$ 0 d. $\frac{1}{849}$ a. $\frac{1}{1800}$ a. $\frac{1}{4287}$	55 65·5 55 55 55·5 55	" " " " " "	·75 1 ·75 ·75 ·75 ·75	18·00 6·31 17·14 23·28 21·82 21·17	20·14 6·74 18·82 20·50 17·45 18·07	Weather fair and calm. Water in the tender cold.
LEEDS. Cylinder . 11 in. Stroke . . 16 in. Wheel . . . 5 ft. Weight . . 7·07 t. Fire-box . . 34·57 sq. ft. Tubes . . . 267·84 sq. ft. Blast-pipe . 2·156 in. Friction . . 85 lbs.							
LEEDS, Aug. 15, 1834, from Liver. to Man., with 20 wag. and tender, 88·34 tons. Gross vaporiz. per hour, 63·18 cubic feet, at the mean velocity of 18·63 miles per hour.	d. $\frac{1}{1094}$ 0 d. $\frac{1}{849}$ a. $\frac{1}{1800}$ a. $\frac{1}{4287}$	54 54·75 54 54 54	" " " " "	·75 ·75 ·75 ·75 ·75	20·72 18·26 24·00 20·34 18·82	22·26 20·25 23·00 19·00 19·60	Weather calm. Water in the tender scarcely tepid.

Date of the experiment, and designation of the engine and its load.	Inclination of the road.	Observed effective pressure in the boiler.	Observed effective pressure in the blast-pipe.	Opening of the regulator, in a fraction of its total size.	Observed velocity, in miles per hour.	Calculated velocity, in miles per hour.	Observations.
		lbs. per sq. inch.	lbs. per sq. inch.		miles.	miles.	
LEEDS, Aug. 15, 1834, from Man. to Liver., with 8 wag. and tender, 39·88 tons, half the road, and 7 wag. and tender, 35·15 tons, the rest of the way. Gross vaporiz. per hour, 68·82 cubic feet, at the mean velocity of 21·99 miles per hour.	d. $\frac{1}{4237}$	51·5	,,	·75	24·54	27·16	Weather fair and calm. Water in the tender very hot. One wag. left behind half way.
	d. $\frac{1}{1800}$	46·5	,,	·75	30·00	28·11	
	a. $\frac{1}{849}$	46·5	,,	·75	25·31	25·25	
	0	46·5	,,	·75	22·50	27·75	
	a. $\frac{1}{89}$	48·5	,,	1	10·00	14·97	
	a. $\frac{1}{1094}$	54	,,	·75	25·71	26·20	
VULCAN. Cylinder 11 in. Stroke . . 16 in. Wheel . . 5 ft. Weight . 8·34 t. Fire-box 34·45 sq. ft. Tubes . . 267·84 sq. ft. Blast-pipe 2·156 in. Friction . 125 lbs.							
VULCAN, July 22, 1834, from Man. to Liver., with 9 first-class coaches and tender, 39·07 tons. Gross vaporiz. per hour, 60·60 cubic feet, at the mean velocity of 22·99 miles per hour.	a. $\frac{1}{89}$	57·5	,,	1	11·42	11·22	Weather calm. Water in the tender hardly tepid.
ATLAS. Cylinder . 12 in. Stroke . . 16 in. Wheel . . . 5 ft. Weight . . 11·40 t. Fire-box . 57·07 sq. ft. Tubes . . . 197·25 sq. ft. Friction . . 139 lbs.							
ATLAS, July 23, 1834, from Liver. to Man., with 40 wag. and tender, 195·5 tons. Gross vaporiz. per hour, 43·81 cubic feet, at the mean velocity of 8·99 miles per hour. Blast-pipe, 2·94 in.	d. $\frac{1}{1094}$	53	,,	1	14·12	13·50	Weather fair and calm. Water in the tender cold. The engine was assisted at starting by two other engines.
	0	53·5	,,	1	9·23	10·05	
	d. $\frac{1}{849}$	53	,,	1	16·21	14·00	
	a. $\frac{1}{1800}$	55	,,	1	8·00	8·38	
	a. $\frac{1}{4237}$	54·5	,,	1	5·87	9·60	

Date of the experiment, and designation of the engine and its load.	Inclination of the road.	Observed effective pressure in the boiler.	Observed effective pressure in the blast-pipe.	Opening of the regulator, in a fraction of its total size.	Observed velocity, in miles per hour.	Calculated velocity, in miles per hour.	Observations.
		lbs. per sq. inch.	lbs. per sq. inch.		miles.	miles.	
ATLAS, Aug. 4, 1834, from Liver. to Man., with 25 wag. and tender, 127·64 tons. Gross vaporiz. per hour, 50·00 cubic feet, at the mean velocity of 15·00 miles per hour. Blast-pipe, 3·06 in.	d. $\frac{1}{1094}$	53	”	1	17·14	16·06	Weather fair a[illegible] calm. Water in the te[illegible] der cold. The connectin[illegible] rods ill-adjus[illegible] The engine w[illegible] into repair th[illegible] next day.
	0	53	”	1	15·00	13·74	
	d. $\frac{1}{849}$	53	”	1	20·52	17·00	
	a. $\frac{1}{1800}$	53·5	”	1	15·38	11·84	
	a. $\frac{1}{4237}$	53	”	1	15·24	12·60	
ATLAS, July 31, 1834, from Man. to Liver., with 8 wag. loaded, 4 empty, and tender, 40·15 tons. Gross vaporiz. per hour, 48·21 cubic feet, at the mean velocity of 15·53 miles per hour. Blast-pipe, 2·94 in.	d. $\frac{1}{4237}$	25	”	1	19·53	19·96	Weather calm. Water in the ten[illegible] der cold.
	d. $\frac{1}{1800}$	25·25	”	1	23·00	20·92	
	a. $\frac{1}{849}$	25·25	”	1	16·08	17·36	
	a. $\frac{1}{89}$	51	”	1	7·50	7·46	
	0	27·25	”	1	16·38	19·41	
	a. $\frac{1}{1094}$	24·75	”	1	15·79	17·57	

CHAPTER XIII.

OF THE PROPORTIONS OF LOCOMOTIVE ENGINES.

SECT. I. *Of the divers problems which occur in the construction of locomotive engines.*

IN the preceding chapter, we have sought the effects producible by a locomotive engine already constructed, or whose dimensions are determined; we are now about to determine, on the contrary, what should be the proportions of a locomotive engine, as yet unbuilt, in order to obtain from it desired effects.

In this state of the question, the quantities given *à priori* are the load of the engine for a known velocity, or else its velocity or its load corresponding to the maximum of useful effect; and the unknown or indeterminate quantities are the heating surface of the boiler, the diameter of the cylinder, the length of the stroke, the diameter of the wheel, and the pressure in the boiler.

On the other hand, we have demonstrated in the preceding chapter, that there exist between these divers quantities, known or unknown, three general analogies expressed by the equations (1 bis), (4 bis), and (5); the first relating to the general effects of

the engine with an indeterminate load or velocity, and the two others to the production of the maximum of useful effect.

From hence then it results that, according as either of these general analogies be taken to determine one or other of the dimensions of the engine, the following are the questions that it may be proposed to resolve:

1st. To determine, either the heating surface of the boiler, or the diameter of the cylinder, or the length of the stroke of the piston, or the diameter of the wheel, that the engine may draw a given load at a desired velocity;

2d. To determine, either the heating surface of the boiler, or the diameter of the cylinder, or the stroke of the piston, or the diameter of the wheel, or, in fine, the pressure in the boiler, that the engine may acquire a desired velocity, or draw a given load, producing at the same time its maximum of useful effect;

3d. To determine the combined proportions proper to be given to the divers parts of the engine, to enable the engine to fulfil divers simultaneous conditions.

Each of these three enunciations visibly comprehends a series of distinct questions, which we shall resolve successively. We shall therefore first suppose that it is required to determine one of the dimensions of the engine, according to the general condition of

its drawing a given load with a given velocity. We shall afterwards pass to similar determinations, deduced from the conditions prescribed for the maximum of useful effect; and finally we shall consider the case in which it is required to determine several of the parts of the engine, from divers conditions relative either to the first case, or to the second.

Sect. II. *Of the vaporization, or of the heating surface, necessary to enable a locomotive engine to draw a given load at a desired velocity.*

Among the questions which we have just indicated, the most important consists in determining the vaporization of the engine, or, in other words, the dimensions proper for its boiler, to enable it to draw a given load at a desired velocity.

To solve the problem, recourse must evidently be had to equation (1 bis), which expresses the general relation between the different dimensions of the engine and its effects, with an indefinite load or velocity. This equation is

$$v = \frac{1}{5280} \cdot \frac{1}{q} \cdot \frac{l}{l+c} \cdot \frac{S}{(1+\delta)\left[(k \pm g)M \pm gm + uv^2\right] + F + \frac{d^2 l}{D}\left(\frac{n}{q} + p + p'v\right)}.$$

Consequently, resolving it with reference to S, which is the required quantity of the problem, we obtain

$$S = 5280\,\frac{l+c}{l}\,q\,(1+\delta)\,v\left[(k \pm g)M \pm gm + uv^2 + \frac{F}{1+\delta} + \frac{d^2 l}{(1+\delta)D}\left(\frac{n}{q} + p + p'\right)\right] \,..(7)$$

Substituting then in this equation for v and M, the given velocity and load, putting likewise, for the dimensions of the engine, their values which may be taken arbitrarily, and, in fine, putting for F the presumed friction of the engine, such as we have given the means of valuing it in Chapter VIII., we shall obtain the *effective* vaporization which the engine ought to have, in order to fulfil the condition prescribed.

Thence must afterwards be deduced the total or gross vaporization of the boiler. Now we have found that in locomotive engines of the present construction, the effective vaporization is to the total vaporization in the ratio of the numbers ·75 and 1. Therefore the total vaporization of water, corresponding to the effective vaporization S, is

$$S' = \frac{S}{\cdot 75} = 1{\cdot}33\ S.$$

And as moreover, in certain engines, there is yet lost, during the motion and by the safety-valves, $\frac{1}{20}$ of the total water vaporized, it follows that for those engines, we shall have the definitive total vaporization of the boiler, on multiplying the quantity just obtained by the factor 1·05; so that the *total* vaporization will then be

$$S' = 1{\cdot}05 \times 1{\cdot}33\ S = 1{\cdot}40\ S.$$

Thus will then be attained the knowledge of the total vaporization necessary to the production of the desired effects. This vaporization will be such as

the engine ought to produce at the given velocity v, and since we have seen that the vaporization varies in the ratio of the fourth roots of the velocities, it follows that at the velocity of 20 miles per hour, the same engine ought to be capable of vaporizing a quantity of water expressed by

$$1{\cdot}40\,S \times \left(\frac{20}{v}\right)^{\frac{1}{4}}.$$

Consequently, if it be desired to conclude from hence the heating surface which the boiler ought to have, it will suffice to refer to the results which we have obtained in Chapter X., namely: that at the velocity of 20 miles per hour, each square foot of *total* heating surface produces a vaporization of ·200 cubic foot of water per hour. Thus the total heating surface necessary to produce the effective vaporization S, at the given velocity v, will be

$$\frac{1{\cdot}40}{{\cdot}20}\,S\left(\frac{20}{v}\right)^{\frac{1}{4}} = 7\,S\left(\frac{20}{v}\right)^{\frac{1}{4}}.$$

If the given velocity v differ but little from 20 miles per hour, or if a very great degree of precision is not required, we may, in this expression, neglect the term

$$\left(\frac{20}{v}\right)^{\frac{1}{4}},$$

and be satisfied with taking the heating surface equal to the quantity 7 S.

It appears at the same time that, in order to obtain immediately the *effective* vaporization of a

given boiler, we may limit the calculation to taking $\frac{1}{7}$ of the total heating surface, expressed in square feet; and the result will be the vaporization expressed in cubic feet of water per hour. This summary method may be used in practice, as an approximation.

Sect. III. *Of the diameter of the cylinders, necessary that the engine may draw a given load at a given velocity.*

If, in planning an engine, the vaporization which the boiler is to have has been previously settled, desired effects may yet be attained by determining for that purpose one of the other dimensions of the engine.

For instance, the diameter of the cylinders, which would enable the engine to fulfil the prescribed conditions, may be sought. To obtain the solution of this problem, it evidently suffices to solve equation (1 bis) with reference to *d*, which is the diameter of the cylinder, and we have

$$d^2 = \frac{D}{l} \cdot \frac{1+\delta}{\frac{n}{q} + p + p'v} \left[\frac{1}{5280} \cdot \frac{l}{l+c} \cdot \frac{S}{(1+\delta)\,qv} - (k \pm g)M \mp gm - uv^2 - \frac{F}{1+\delta} \right] \dots (8)$$

Substituting in this equation, for S, v, M, D and l, the values that have been previously fixed on, introducing for F the presumed friction of the engine, such as we have found it in Chapter VIII., and for $p'v$ the pressure in the blast-pipe, resulting

from the proportions adopted, we shall obtain in the second member the value of d^2, taking the square root of which we have definitively the value of d, or the diameter of the cylinder expressed in feet.

It is to be remarked that the proposed problem will be possible only when

$$\frac{1}{5280}\cdot\frac{l}{l+c}\cdot\frac{1}{q}\cdot\frac{1}{1+\delta}\cdot\frac{S}{v} > (k \pm g)\,M \pm gm + uv^2 + \frac{F}{1+\delta},$$

or

$$S > 5280\,\frac{l+c}{l}\,(1+\delta)\,qv\left[(k \pm g)\,M \pm gm + uv^2 + \frac{F}{1+\delta}\right];$$

for otherwise the second member of the equation would become negative, and the value of d would be imaginary. This condition is readily explained on referring to the general value of the vaporization necessary to draw the load M at the velocity v. This general value is, as has been seen, according to equation (7),

$$S = 5280\,\frac{l+c}{l}\,q(1+\delta)v\left[(k \pm g)M \pm gm + uv^2 + \frac{F}{1+\delta} + \frac{d^2 l}{(1+\delta)D}\left(\frac{n}{q} + p + p'v\right)\right],$$

and it is manifest, on the mere inspection, that if the value supposed for S did not fulfil the condition indicated above, the vaporization would be insufficient to draw the load M at the velocity v, whatever might be the diameter chosen for the cylinder. The impossibility of the problem would arise then from the values adopted for S, M and v being incompatible with each other; but on taking a sufficient value for S, the required solution will be easily attained, by means of the preceding formula.

SECT. IV. *Of the length of the stroke of the piston, requisite for the engine to draw a given load at a given velocity.*

If, besides the vaporization of the boiler, the diameter of the cylinder has also been fixed upon, but that nothing has been decided relative to the stroke of the piston, the value of this undetermined quantity may still be obtained, such as to enable the engine to fulfil the desired conditions.

To obtain the length of stroke proper for an engine, entirely determined in other respects, in order that it may draw a desired load at a given velocity, it will be sufficient to resolve equation (1 bis) with reference to l, which will give

$$l=\frac{D}{d^2}\cdot\frac{1+\delta}{\frac{n}{q}+p+p'v}\left[\frac{1}{5280}\cdot\frac{l}{l+c}\cdot\frac{1}{q}\cdot\frac{1}{1+\delta}\cdot\frac{S}{v}-(k\pm g)M\mp gm-uv^2-\frac{F}{1+\delta}\right]\ldots(9)$$

This equation then will solve the question, and it will be remarked that, to prevent l from becoming a negative quantity, the value of S must fulfil the same condition as in the preceding inquiry, which is explained in the same manner.

The presumed friction F of the engine, and the pressure $p'v$ in the blast-pipe, which are to be substituted in the equation, will be obtained as it has been said in the last section.

SECT. V. *Of the diameter of the wheel, necessary for the engine to attain a desired velocity with a given load.*

In fine, it may still occur that from different considerations all the other proportions of the engine have been decided on, and that with these proportions it be required to know, what diameter should be given to the propelling wheel of the engine, that it may acquire a desired velocity with a given load.

The quantity D in this case becomes the object of determination of the problem, and its value will again be drawn from equation (1 bis), namely:

$$D=\frac{d^2 l}{1+\delta}\cdot\frac{\frac{n}{q}+p+p'v}{\frac{1}{5280}\cdot\frac{l}{l+c}\cdot\frac{1}{q}\cdot\frac{1}{1+\delta}\cdot\frac{S}{v}-(k\pm g)M\mp gm-uv^2-\frac{F}{1+\delta}} \quad \ldots (10)$$

It will be remarked that this equation, like the two preceding ones, is also subject to the condition that the vaporization adopted for the engine be not incompatible with the load and the velocity which are intended for it at the same time; and it is, of course, needless to add, that if the value of D resulting from this formula should be found too large or too small to be applicable in practice, the solution obtained must be regarded merely as satisfying the algebraic equation, but by no means as solving the practical problem in the manner it ought to be understood.

Sect. VI. *Of the vaporization, or of the heating surface a locomotive engine ought to have, in order to acquire a given velocity, producing at the same time its maximum of useful effect.*

The four questions which have occupied us thus far, have had in view to determine one or other of the dimensions of the engine, from equation (1 bis), that is, from the condition that the engine draw any given load whatever, at a given velocity. But we are now about to suppose that it is required to determine the dimensions of the engine, not from its effects with any given load, but from the condition that it produce its maximum useful effect, either at a given velocity, or with a given load; and as the relation between the dimensions of the engine and its maxima effects is expressed by the two equations (4 bis) and (5), namely:

$$v' = \frac{1}{5280} \cdot \frac{S}{d^2} \cdot \frac{D}{l+c} \cdot \frac{1}{n+q\,P},$$

$$M' = \frac{d^2 l}{(1+\delta)(k \pm g)D}(P - p - p'v') - \frac{1}{k \pm g}\left(\frac{F}{1+\delta} + uv'^2 \pm gm\right),$$

to these we must have recourse in order to attain the solution sought.

Suppose, then, it be required to determine the vaporization S, or, in other words, the heating surface of the engine, according to the condition that it produce its maximum of useful effect at a certain given velocity v'.

It is clear, then, that the value of S must be derived from equation (4 bis), which will give

$$S=5280 \frac{l+c}{l} \cdot \frac{d^2 l}{D} \cdot qv' \left(\frac{n}{q}+P\right) \ldots\ldots (11)$$

This equation will make known the effective vaporization sought, as soon as v and the dimensions of the engine shall be replaced by their values supposed fixed or chosen beforehand; and from it will be concluded, as in Sect. I. of this chapter, the total consumption of water in the boiler, and consequently the heating surface necessary to obtain the desired effect.

It will be remarked that, as equation (5) furnishes no relation between the vaporization S and the maximum load of the engine, the vaporization cannot be determined directly, from the condition of the engine drawing a certain given load, producing at the same time its maximum useful effect. It is evident, indeed, that as this condition depends entirely on the effort the engine is capable of exerting, and is altogether independent of the velocity of the motion, the question is to be solved only by seeking the pressure of the steam in the boiler, capable of producing the determined effort; and consequently it is in the next problem that its solution will be found.

SECT. VII. *Of the pressure in the boiler necessary for the engine to draw a given load, or acquire a desired velocity, producing at the same time its maximum of useful effect.*

If the maximum load of the engine, or, in other words, the load it should draw when producing its maximum of useful effect, have been previously decided on, and if it be desired to know what ought to be the pressure in the boiler, to enable the engine to draw that maximum load, it is clearly to equation (5) that recourse must be had, since that is precisely the equation which gives the relation between the known and unknown quantities of the problem under consideration.

Resolving then this equation with reference to P, which is the pressure in the boiler, we obtain

$$P=(1+\delta)\frac{D}{d^2 l}\left[(k\pm g)\,M'\pm gm+uv'^2+\frac{F}{1+\delta}\right]+p+p'v' \quad \ldots \quad (12)$$

This formula then will make known the pressure P.

It is to be observed only that this equation contains two terms $p'v'$ and uv'^2, functions of the minimum velocity of the engine, which is not given *à priori*, but which is, on the contrary, to result from the knowledge of P, according to the equation (1 bis), when that quantity P shall be determined. This circumstance therefore will render it necessary to operate here in the same manner as we have already indicated relatively to equation (1), in the

preceding chapter; that is to say, the operation must be performed by successive approximations. A supposition therefore must first be made as to the probable value of v', and having calculated, with that supposition, the value of P, it must be ascertained, by seeking the velocity of maximum useful effect for the pressure P and the known vaporization S of the engine, whether that velocity be too remote from that which was supposed for the finding of P. If the difference between the two is trifling, this first solution will suffice, and the value thus obtained for P may be adopted. If, on the contrary, the velocity of maximum useful effect, resulting from the values of P and S, differ from the supposition originally made, too much to warrant placing confidence in the result, then the calculation must be begun anew, introducing into the equation (12) the velocity v' obtained by this first approximation, and thence will be deduced a new value of P more approximate than the first. This would lead, if required, to a third approximation; but with a little experience, two trials will always lead to a value of P sufficiently near for practical uses. The problem therefore may be somewhat long to solve, but can present no sort of difficulty.

The solution thus obtained will give the *total* or absolute pressure of the steam in the boiler, expressed in pounds per square foot; that is, expressed generally in units of the species of those which are determined by the homogeneity of the

equations, as has been explained in Sect IV. of the preceding chapter.

Instead of determining the pressure in the boiler, as we have just done it, that is, according to the condition that the engine draw a given load, producing at the same time its maximum of useful effect, we may likewise determine that pressure, according to the condition that the engine shall, with a fixed vaporization, attain a certain given velocity, producing also its maximum of useful effect.

It will then be from equation (4 bis) that the value of P must be drawn, which gives

$$P = \frac{1}{5280} \cdot \frac{1}{q} \cdot \frac{l}{l+c} \cdot \frac{D}{d^2 l} \cdot \frac{S}{v'} - \frac{n}{q} \quad \ldots\ldots (13)$$

And substituting in this equation the value of the divers dimensions of the engine, we have the pressure in the boiler, which, for a given vaporization, will make the engine assume the desired velocity v', producing at the same time its maximum useful effect.

SECT. VIII. *Of the diameter of the cylinder, or of the stroke of the piston, or of the diameter of the wheel, necessary that an engine may assume a desired velocity or draw a given load, producing also its maximum useful effect.*

It has been seen in the two preceding problems, that if the engine is required to assume a given

velocity, producing at the same time its maximum of useful effect, there are two ways of attaining that end: either by determining the vaporization necessary for the producing of that effect, or by assuming any vaporization, and then determining the pressure in the boiler proper to obtain the desired velocity.

We have just seen likewise, that if it be wished to render the engine capable of drawing a certain given *maximum* load, that end may be attained by determining, from equation (12), the pressure which ought then to be produced in the boiler.

But besides these means of attaining the desired effects, there are yet three other ways, which consist in adopting arbitrarily the vaporization of the engine and the pressure in the boiler, and then determining either the diameter of the cylinder, or the stroke of the piston, or the diameter of the wheel, according to the condition proposed to be fulfilled.

Suppose then that the vaporization of the engine and the pressure of the boiler be already fixed by other considerations, and that it be required of the engine to produce its maximum useful effect at a certain fixed velocity v'. Then it will clearly suffice to resolve the equation (4 bis) with reference to d, to l, or to D, according to which of those three quantities it is wished to determine from that condition. We shall have then

$$d^2 = \frac{1}{5280} \cdot \frac{l}{l+c} \cdot \frac{1}{q} \cdot \frac{D}{l} \cdot \frac{S}{v'} \cdot \frac{1}{\frac{n}{q}+P}, \quad \ldots . \, (14)$$

or

$$l=\frac{1}{5280}\cdot\frac{l}{l+c}\cdot\frac{1}{q}\cdot\frac{D}{d^2}\cdot\frac{S}{v'}\cdot\frac{1}{\frac{n}{q}+P},\ \ldots\ldots (15)$$

or

$$D=5280\,\frac{l+c}{l}\cdot qd^2l\cdot\frac{v'}{S}\cdot\left(\frac{n}{q}+P\right)\ \ldots\ldots (16)$$

We may therefore choose one of these three solutions; and introducing into the equations for S, P, and the dimensions of the engine, their values previously decided on, we shall obtain the value of those dimensions which shall have been left to determine according to the prescribed condition.

If, instead of laying down the condition that the engine acquire the velocity v' producing also its maximum useful effect, we, on the contrary, impose the condition that it draw a certain given maximum load M′, then the problem will be the same as the preceding, with the exception that M′ will be given instead of v'. Recourse therefore will be had to equation (5), which, resolved successively with reference to d, l and D, will give

$$d^2=(1+\delta)\frac{D}{l}\cdot\frac{(k\pm g)\,M'\pm gm+uv'^2+\frac{F}{1+\delta}}{P-p-p'v'},\ \ldots\ldots (17)$$

or

$$l=(1+\delta)\,\frac{D}{d^2}\cdot\frac{(k\pm g)M'\pm gm+uv'^2+\frac{F}{1+\delta}}{P-p-p'v'},\ \ldots\ldots (18)$$

or, in fine,

$$D=\frac{d^2\,l}{1+\delta}\cdot\frac{P-p-p'v'}{(k\pm g)M'\pm gm+uv'^2+\frac{F}{1+\delta}}\ \ldots\ldots (19)$$

As these equations still contain the terms $p'v'$ and uv'^2, which are functions of the velocity v', and as the latter is not yet known, but must on the contrary result from the previous knowledge of d, l or D, the proceeding here will be by successive approximations, as we have indicated above, in Sect. VII.

Sect. IX. *Of the combined proportions to be given to the parts of an engine, to enable it to fulfil divers simultaneous conditions.*

In all the preceding problems we have supposed that all the dimensions of the engine, except one, are assumed at will, and that this one dimension is afterwards determined according to some condition imposed as to the work of the engine. But as in the general problem of the construction of an engine, there are five indeterminate quantities, namely: the heating surface, or, in other words, the vaporization, the pressure in the boiler, the diameter of the cylinder, the length of the stroke of the piston, and the diameter of the wheel, it is evident that five simultaneous conditions may be prescribed, for the engine to fulfil, and that on determining each of the said dimensions according to those conditions, the engine will be capable of fulfilling them all successively, according to the circumstances in which it is placed.

The conditions that may be prescribed, to deter-

mine the dimensions of the divers parts of the engine, consist in fixing the different effects it ought to produce under certain circumstances; and these effects themselves depend on three quantities that may be assumed at will; namely, the velocity for any given load whatever, the velocity of maximum useful effect, and the maximum load, or load of maximum useful effect.

As many as five values then of these different quantities may be assumed, and the five dimensions of the engine may be determined according to them; or four only of those values may be assumed, and four of the dimensions of the engine determined from them, the fifth then remaining to be chosen arbitrarily; or, in fine, three or two, or even one only of those conditions may be assumed, and the same number of dimensions determined, the others remaining either to be taken arbitrarily or to be determined from considerations of a different nature.

It is obvious that a considerable number of problems may be proposed on this subject; but they never present any difficulty. It will suffice, in effect, to recur to equations (1 bis), (4 bis), and (5), and to express that they exist at the same time, for the given values of the quantities M, v, M$'$, v'. Then will be drawn from them, by elimination, the value of each of the required dimensions of the engine.

We will not undertake to solve all the problems that may be thus proposed; but to show the manner

of the proceeding, we will choose one or two among those which may occur most frequently.

Suppose it be desired to build an engine capable of drawing, on a given inclination, a certain determined maximum load M′, and, at the same time, of acquiring on another inclination, a certain given velocity v, with another load M likewise known.

We have then at the same time the two equations (4 bis) and (1 bis), or

$$M' = \frac{d^2 l}{(1+\delta)(k \pm g) D}(P - p - p'v') - \frac{1}{k \pm g}\left(\frac{F}{1+\delta} + uv'^2 \pm gm\right),$$

$$v = \frac{1}{5280} \cdot \frac{1}{q} \cdot \frac{l}{l+c} \cdot \frac{S}{(1+\delta)[(k \pm g)M \pm gm + uv^2] + F + \frac{d^2 l}{D}\left(\frac{n}{q} + p + p'v\right)}.$$

These may, consequently, be used to determine, for instance, the diameter of the cylinder from the first condition, and the heating surface from the second. The first equation therefore must be resolved with reference to d, and the second with reference to S. This is what we have already done in the Sections VIII. and II., having obtained the equations (17) and (7), namely:

$$d^2 = (1+\delta)\frac{D}{l} \cdot \frac{(k \pm g) M' \pm gm + uv'^2 + \frac{F}{1+\delta}}{P - p - p'v'}, \quad \ldots \quad (17)$$

$$S = 5280 \frac{l+c}{l} q (1+\delta) v \left[(k \pm g) M \pm gm + uv^2 + \frac{F}{1+\delta} + \frac{1}{1+\delta} \cdot \frac{d^2 l}{D}\left(\frac{n}{q} + p + p'v\right)\right] \ldots (7)$$

Thus, introducing into equation (17), the given value for M′, we first deduce the value of d, as has been explained Sect. VIII.; and then sub-

stituting that value in the equation (7), with the given quantities v and M, we shall conclude the vaporization S, which the engine ought to have to enable it to fulfil the prescribed condition.

It is evident that the problem which we have just proposed, would occur on a railway on which it were desired, 1st, to establish on a level a certain regular velocity v, with a fixed load M; and 2ndly, to enable the engines to ascend without assistance, and with the same load, a known acclivity contained in the distance to be traversed.

Suppose, for instance, it were desired to build an engine of the weight of about 8 tons, capable of drawing, at the velocity of 25 miles per hour, upon a level, a load consisting of 10 waggons weighing 56 tons gross, tender included, and to ascend with the same load a plane inclined $\frac{1}{184}$. First, in equation (7) we shall make $M = 56$, $g = 0$, $v = 25$; then in equation (17) we shall make $M' = 56$ and $g = \frac{2240}{184} = 12{\cdot}174$ lbs., and we shall give at the same time to v' a value by supposition, as 16 miles, for instance, which is afterwards to be verified.

Performing the calculation then with these data, and moreover taking arbitrarily the stroke of the piston at 16 inches, or $l = 1{\cdot}33$ foot, the diameter of the wheel $D = 5$ feet, and the pressure in the boiler at 65 lbs. per square inch, or $P = 65 \times 144 = 9360$ lbs. per square foot, there will result

$$d = 11 \text{ inches},$$

$$S = 51{\cdot}18 \text{ cubic feet of water per hour.}$$

From the mode of calculation and the equation employed, it is clear that the quantity S represents the *effective* vaporization, at the velocity of 25 miles per hour. Hence therefore will be concluded, first, 48·40 cubic feet for the *effective* vaporization, and 65 cubic feet for the *total* vaporization, at the velocity of 20 miles per hour.

This determination being effected, it must be ascertained whether the value of 16 miles per hour, which has been supposed for v', does in effect suit the vaporization found; which in the present example it does. Should it be perceived that the first valuation of v' has been made too high or too low, the calculation must be repeated, assuming for v' a more proximate value.

Finally, referring to what has been said in Sect. II. of this chapter, we shall find 325 square feet for the total heating surface of the boiler corresponding to the vaporization of 65 cubic feet of water; and it would be necessary to extend that surface to 350 square feet, were there any apprehension of the engine being liable to lose steam permanently by the safety-valves.

It is plain that, in the above problem, instead of determining the diameter of the cylinder from the first-prescribed condition, we might have determined, either the pressure in the boiler, or the stroke of the piston, or the diameter of the wheel; and then, instead of employing equation (17), recourse would have been had to equations (13), (18), or (19). The

calculation then would have remained entirely the same, and the solution would obviously not have presented more difficulty.

As a second example, we will suppose it be required to construct an engine, capable of drawing, 1st, a certain given load M_1 at a desired velocity v_1, on a plane of known inclination, the gravity on which shall be expressed by g_1; and 2ndly, another given load M_2 at a velocity likewise known v_2, on another inclined plane whereon the gravity shall have the value g_2.

Here it is plain that the equation (1 bis) or (7), which refers to the effects of the engine with indefinite load or velocity, will subsist if we introduce into it successively M_1, v_1, and g_1, M_2, v_2 and g_2, in place of the general values M, v and g. Consequently there will result, for the solution of the problem, the two conditional equations

$$S = 5280 \frac{l+c}{l} q(1+\delta)v_1 \left[(k \pm g_1)M_1 \pm g_1 m + u v_1^2 + \frac{F}{1+\delta} + \frac{1}{1+\delta} \cdot \frac{d^2 l}{D} \left(\frac{n}{q} + p + p' v_1\right)\right],$$

$$S = 5280 \frac{l+c}{l} q(1+\delta)v_2 \left[(k \pm g_2)M_2 \pm g_2 m + u v_2^2 + \frac{F}{1+\delta} + \frac{1}{1+\delta} \cdot \frac{d^2 l}{D} \left(\frac{n}{q} + p + p' v_2\right)\right].$$

By means then of these two equations, any two of the dimensions of the engine may be determined, and the other three assumed arbitrarily. We may, for instance, previously choose, from other considerations, the pressure in the boiler, the diameter of the cylinder, and the length of stroke of the piston, and determine the diameter of the wheel and the vaporization from the two conditions imposed.

Then, introducing into the above equations, for the given loads and velocities and the dimensions chosen, their numerical values, those equations will contain but two unknown quantities, which will easily be deduced from them by elimination.

Thus this problem would be as easy as the preceding one, and it would be the same with any other combination of conditions that might be imposed to determine the proportions of the engine. For this reason we shall dwell no longer on these researches.

SECT. X. *Of the special influence of each of the dimensions of the engine on the effects produced.*

It remains, in fine, as a general conclusion of the preceding researches, to specify the peculiar influence of each of the dimensions of the engine on the effects which are to be expected from it. This inquiry will serve to establish fixed notions as to the dimensions most favourable for the producing of the divers effects that may be required of engines about to be constructed.

1st. Examining equation (1 bis), namely,

$$v = \frac{1}{5280} \cdot \frac{1}{q} \cdot \frac{l}{l+c} \cdot \frac{S}{(1+\delta)\left[(k \pm g)M \pm gm + uv^2\right] + F + \frac{d^2 l}{D}\left(\frac{n}{q} + p + p'v\right)},$$

it will easily be recognised that the velocity of the engine with a given load M, will be by so much the greater, all things else being equal, as the vaporization S is greater. Moreover, it will also be recog-

nised that, for a given vaporization, the velocity will be by so much the greater as the factor

$$\frac{d^2 l}{D}$$

has less value. It is in consequence to be concluded that, in order to augment to the utmost the velocity of an engine with a given load, we must either employ a cylinder of the smallest possible diameter, or make the wheel the largest possible with reference to the stroke of the piston.

These consequences might however have been seen *à priori;* for if we suppose a given vaporization in the boiler, it is clear that the quantity of steam which will result from it per minute cannot issue forth in the same time, by a cylinder of less diameter, except on the condition of increasing its velocity during its efflux, that is, of increasing the velocity of the piston. As to the ratio between the length of the stroke of the piston and the diameter of the wheel of the engine, as it is known that at every double stroke of the piston the engine advances one turn of the wheel, it is readily perceived that the larger the wheel relatively to the stroke of the piston, the greater must be the velocity of the engine with a given load. This latter circumstance shows also that in order to increase the velocity of an engine, it is not absolutely necessary to augment the diameter of the wheel; for the same end will be attained by diminishing the stroke

of the piston. Thus, on railways of small width of way, and on which in consequence it would not be advisable to introduce wheels of too great a diameter, a considerable velocity may be attained by proportionally diminishing the stroke of the piston; but this disposition has the inconvenience of rendering the velocity of the piston much greater for the same velocity of the engine. For this reason, when more velocity is desired, the better way is always to increase the vaporization; which beyond certain limits requires more width of way.

2nd. Referring to equation (2), which gives the load the engine is capable of drawing at a desired velocity, namely:

$$M = \frac{1}{(1+\delta)(k \pm g)}\left[\frac{1}{5280} \cdot \frac{l}{l+c} \cdot \frac{S}{qv} - \frac{d^2 l}{D}\left(\frac{n}{q} + p + p'v\right) - F\right] - \frac{1}{k \pm g}(uv^2 \pm gm),$$

and making, in order to simplify, $g = 0$, that is, supposing the train to be drawn upon a level, it will be recognised that the load is by so much the greater as the vaporization S of the engine, that is the heating surface of the boiler, is greater; and that, on the contrary, it is diminished by the values of d, l and D, that is, by the dimensions of the cylinder, the stroke of the piston, and the wheel, which are proper to augment the velocity of the engine.

Thus an increase of the heating surface of the boiler tends to augment both the velocity and the load of the engines, but a change in the diameter of the cylinder, the length of the stroke and the

diameter of the wheel, is favourable to the velocity only at the expense of the load; and if it be desired that the engine should draw a considerable load at a given velocity, it must have a large cylinder, a long stroke of the piston, and a wheel of small diameter. This circumstance explains itself easily, on considering first that the greater the diameter of the cylinder, the greater is the effort exerted by a given pressure of the steam. As to the influence of the proportion of the stroke of the piston to the diameter of the wheel, it evidently results from this, that the power of the steam acts at the extremity of the radius of the crank of the axle, which is equal to the half stroke of the piston, whereas the resistance of the load acts at the extremity of the radius of the wheel; and it is well known that a force is by so much the greater as it acts on a greater lever; whence results that the longer the stroke of the piston with reference to the wheel, the more advantage has the power over the resistance.

3rd. Examining the value of the useful effect produced by the engine at a given velocity, namely, from equation (3):

$$\text{u. E.} = \text{M}v = \frac{1}{(1+\delta)(k \pm g)}\left[\frac{1}{5280}\cdot\frac{l}{l+c}\cdot\frac{\text{S}}{q} - \frac{d^2 lv}{\text{D}}\left(\frac{n}{q}+p+p'v\right) - \text{F}v\right] - \frac{v}{k \pm g}(uv^2 \pm gm)$$

and supposing, in order to simplify, $g = 0$, we find that this useful effect is augmented, precisely by the same causes as the load of the engine; so that it increases with the vaporization of the boiler, but on

the contrary is diminished by the dimensions of the cylinder, the stroke of the piston, and the wheel, which tend to increase the velocity of the motion.

The divers expressions of the useful effect necessarily offer analogous variations, that is to say, the dimensions which tend to augment the load will have also the result of augmenting the effect of the engine, in horse-power, the useful effect produced per pound of fuel and per cubic foot of water vaporized, and they will diminish the quantity of coke and water necessary to produce the effect of one horse, or to draw a ton one mile.

4th. If we now seek what influence the proportions of the engine will have on its divers effects, the engine producing at the same time its maximum useful effect, we first find that, since the velocity of *maximum* useful effect is expressed by the equation (4 bis), or

$$v' = \frac{1}{5280} \cdot \frac{S}{d^2} \cdot \frac{D}{l+c} \cdot \frac{1}{n+qP},$$

it is clear that this velocity will be augmented by the vaporization of the boiler, as well as by those values of d, l and D, which produce a similar effect on the general velocity of the engine. Moreover, it is recognised also that the greater the pressure in the boiler, the less will be the velocity of the maximum useful effect of the engine; which arises from the circumstance that the steam is less in volume as its pressure is greater.

5th. Equation (5), which gives the maximum load of the engine,

$$M' = \frac{d^2 l}{(1+\delta)(k \pm g) D} (P - p - p'v') - \frac{1}{k \pm g} \left(\frac{F}{1+\delta} + nv'^2 \pm gm \right).$$

shows that the maximum load of the engine is totally independent of the vaporization in the boiler, and that for given dimensions of the engine, it increases precisely when the pressure P of the steam in the boiler increases; and this effect is owing to the atmospheric pressure then neutralizing a fraction by so much the less of the effort applied by the engine. As for the rest, the maximum load is likewise, as in the general case, diminished by the dimensions of the engine, which tend to increase the velocity.

6th. Referring to the general conclusions deduced from the examination of equation (3), which were these, that all the dimensions proper to diminish the velocity of the engine, have also the result of augmenting its useful effect, it will be recognised that, since the case of maximum useful effect is but a particular case of the general one, it must necessarily be subject to the general conditions already expressed. Consequently the maximum useful effect of the engines will be augmented by the same causes which increase the maximum load, that is to say, by the increase of the pressure in the boiler, by that of the diameter of the cylinder or of the length of the stroke of the piston, and

in fine, by the diminution of the diameter of the wheel.

7th. Lastly, on examining equation (7), which gives the vaporization of the engine, necessary to draw a given load at a desired velocity, namely:

$$S = 5280 \frac{l+c}{l} q(1+\delta)v \left[(k \pm g)M \pm gm + uv^2 + \frac{F}{1+\delta} + \frac{1}{1+\delta} \cdot \frac{d^2 l}{D}\left(\frac{n}{q} + p + p'v\right)\right],$$

it is recognised that the vaporization increases with the factor

$$\frac{d^2 l}{D};$$

that is to say, it is so much the greater as the diameter of the cylinder and the length of the stroke are greater, and that it is on the contrary diminished by an increased diameter of the wheels of the engine.

SECT. XI. *Of the comparative effects of locomotive engines upon the wide-gauge and narrow-gauge railways.*

We have just seen in the preceding paragraphs, that the only means of really increasing the effects of the engines consists in augmenting their vaporization, that is, the heating surface of their boiler, because this mode produces an increase of velocity without prejudice to the load of which the engines are capable. On the other hand, it is easy to conceive that on a railway of given width, the dimen-

sions of the engines cannot be augmented indefinitely. It is necessary then to examine here how the width of way may limit the size of the boilers, and consequently the power of locomotives.

Almost all the railways of great traffic have been hitherto laid down of the width of 4 feet 8½ inches, which dimension was founded merely on custom. In 1836, when the Great Western Railway was made to form the communication between London and Bristol, Mr. Brunel, jun., made the road 7 feet in width. The question is now to examine what advantages may result, with regard to the velocity and the useful effects of the engine, from this widening of the road.

It has been seen above that the locomotives employed on the Liverpool and Manchester Railway vaporize on an average 65 cubic feet of water per hour, and this railway is 4 feet 8½ inches wide. On the London and Birmingham, which is of the same width, there are locomotives which vaporize as much as 100 cubic feet of water per hour, and it would be difficult to establish engines having a greater vaporizing power on railways of this dimension, because the width of the way would very hardly admit of a farther augmentation of the dimensions of the boiler. On railways then of this width, locomotives of 65 cubic feet of vaporization may be considered as engines of medium force, and engines of 100 feet of vaporization, as nearly the most powerful that it is possible to have.

On the Great Western Railway, which is 7 feet in width, the engines of medium force vaporize about 120 cubic feet of water per hour, and the most powerful in use vaporize as much as 200 cubic feet; but considering the interval which remains between the boiler and the frame-work of the engine, there is room to think that, on this line, engines might be established of 300 cubic feet of vaporization, and even more, without very considerably augmenting the weight of the engine.

If then, by means of the formulæ developed in the preceding chapter, we seek the velocity and effects which these different species of engines are capable of producing, we shall form the Table that will be presented a little further on.

To perform this calculation, we proceed as was done in Article III. of the preceding chapter, in which the examples reported offer precisely the results proper to the engines of medium force employed on the two widths of way under consideration. Thus we adopt the dimensions of the engines and the pressure of the steam admitted on each railway; we take the presumed friction of the engines at 15 lbs. per ton of their weight, as we have deduced it from our own researches in Chapter VIII. Similarly, from what experience has proved, we take the consumption of fuel per cubic foot of water vaporized, at 9·2 lbs. for engines of 65 cubic feet of vaporization, at 8 lbs. for those of 100 cubic feet, and in fine, at 8·8 lbs. for engines of 120 cubic

feet, 200 cubic feet and above, though it would appear that the consumption of these latter engines ought to be less, because the size of the boiler is always favourable to the saving of fuel. To take account of the variation of vaporization with the velocity, we likewise adopt, according to experiment, the vaporizations above indicated as those which refer to the respective velocities of 20, 30, 25, and 35 miles per hour, for the different engines, taking them in the order in which we have placed them. We value the surface of the carriages according to what has been indicated in the two examples of Article III. of the preceding chapter; and finally, we neglect, for all the engines, the loss of steam which may take place by the safety-valves, because we suppose this loss corrected in all, or at least in proportion to the total vaporization, and that the divers effects produced will therefore, by that cause, be all reduced in a proportional degree.

To establish the comparison of the different engines on the most usual load, for the conveyance of passengers, we shall seek the velocity and the consumption of coke of each engine with a train of 50 tons gross, tender *not* included; and in the last column we shall add the *maximum* velocity that the engine is capable of acquiring, drawing its tender alone and without any other load.

Comparative Table of the velocity and effects of locomotive engines on narrow-gauge and on wide-gauge railways.

Number showing the order of the engine.	Designation of the way.	Designation of the engine.	Vaporisation, in cubic feet of water per hour.	Diameter of the cylinder.	Stroke of the piston.	Diameter of the wheel.	Weight of the engine.	Velocity with a load of 50 tons gross, tender not included.	Coke per ton gross per mile, with the load of 50 tons gross.	Maximum velocity, or velocity with no other load than the tender.
			cubic feet.	inches.	inches.	feet.	tons.	miles per hour.	lbs.	miles per hour.
I.	Narrow-gauge.	Of the Liverpool and Manchester Railway	65	11	16	5	8	25·10	·47	35·03
II.	do.	Of the London and Birmingham Railway	100	12	16	5	11	30·36	·53	41·01
III.	Wide-gauge.	Of the Great Western Railway	120	14	16	8	18	34·75	·60	43·28
IV.	do.	do.	200	16	16	7	18	40·47	·87	50·15
V.	do.	do.	200	14	16	8	18	44·25	·80	55·86
VI.	do.	do.	300	14	16	8	20	55·23	·96	69·15

Such are then the effects which are to be expected from these different kinds of locomotive engines; and the results which we have just signalized for the engines of the London and Birmingham, and Great Western Railways, will be found sufficiently confirmed by the experiments made in 1838, on those two railways, at the request of the Directors of the Great Western, when some difficulty arose respecting the width of way.[1] Taking the mean of such of these experiments as were made on trains of about 50 tons, having regard to the average vaporization effected during the trip, and adding an experiment recently published by the Directors themselves of the Great Western Railway, in which an engine, similar to that of No. II. of the preceding Table, drew a load of 43 tons gross, tender not included, at the velocity of 38 miles per hour, consuming ·95 ℔. of coke per ton per mile, it will be recognised that the results indicated by the calculation, for the locomotives Nos. V. and VI., which have never been built, by no means exceed the effects which may be expected from those engines. As to the possibility of attaining velocities of 50 and 60 miles per hour, with locomotives of sufficient vaporizing power, we deem it completely proved by an experiment of our own, made on the 3rd August, 1839, on the Great Western Railway, with Mr. Daniel Gooch, one of

[1] Nicholas Wood's Report to the Directors of the Great Western Railway.

the Company's engineers. In this experiment, the engine EVENING STAR, built by Mr. Robert Stephenson of Newcastle, drawing only the tender loaded with eight persons, repeatedly attained the velocity of 55·4 miles per hour; and if the feeding-pipes of the boiler had not been too small for that velocity, an arrangement which has since been altered, there is no doubt that we should easily have maintained that velocity throughout the trip, and even have exceeded it; but as those pipes could not supply the expenditure of the boiler, the water in the latter lowered rapidly, and having once attained the velocity mentioned, we were obliged to close the regulator and let the engine run, without working, to give time for the boiler to fill again. The results deduced from our formulæ and contained in the Table presented above, appear then to us to be completely supported by the facts.

Thus it is manifest that locomotive engines on wide-gauge railways can draw the same average load of 50 tons, or about 200 passengers, at much greater velocities than the engines on narrow-gauge railways, and that the velocity of the former may even amount to double the velocity of the latter. Such an advantage is certainly not to be neglected, and it would be vain to object that the present velocity is sufficient; for that argument might have been urged, either some years ago against the establishment of mail-coaches, or in our days against any establishment of railways whatever.

It will be remarked, in the preceding results, that the surplus velocity is purchased by a greater expense of fuel. This surplus of expense arises undoubtedly in part from the excessive weight of the engine and its tender, which together amount to about 30 tons, instead of 15, which is the corresponding weight for engines on narrow-gauge railways; so that, for a load of 50 tons, the motive power is affected with a weight of 30 tons in the one case, and with a weight of but 15 tons in the other. But that effect depends also especially on the circumstance, that the resistance of the air, the pressure in the blast-pipe, and the other passive resistances, consume quantities of work by so much the greater as the motion is performed with greater velocity. It is then an inevitable result of the velocity, whatever may be the width of way, and the engine employed. To obtain conviction moreover that the inconvenience of the greater weight of the mover may be counterbalanced by opposite advantages, it suffices to compare the two species of engines at the same velocity. Now, calculating the load that a wide-gauge locomotive engine of medium force, or of 120 cubic feet of vaporization, can draw at a velocity of about 25 miles per hour, we find, as may be seen in the example calculated in Article III. of the preceding chapter, that that load will be 147 tons, tender included, or 137 tons without the tender, and that the corresponding consumption of fuel will be ·30 lb. of coke per

ton per mile. Comparing then this effect to that of an engine of medium force of the narrow-gauge, or of 65 cubic feet of vaporization, we have the following results:

	Velocity, in miles per hour.	Load, in tons gross, tender not included.	Coke, in lbs. per ton per mile.
Engine of 65 cubic feet of vaporization, narrow-gauge	25·10	50	·47
Engine of 120 cubic feet of vaporization, wide-gauge	25·55	137	·30

Consequently, when a velocity of 25 miles per hour is considered sufficient, it is obvious that wide-gauge locomotive engines have the advantage of conveying much greater loads, and consuming less fuel per ton.

We are then of opinion, that in countries where as yet but few railways are made, it is worth considering whether, according to the circumstances, it will not be advantageous to employ a greater width of way than that in general use, and we must here add that, for the most powerful engines of the above Table, a way 6½ English feet in width appears to be sufficient.

Sect. XII. *Practical formulæ, to determine the proportions of locomotive engines, according to given conditions.*

Before terminating this chapter, we will here give, in their numerical form, all the formulæ which we have just presented, to determine the propor-

tions of the engines, according to given conditions. For the signification of the signs employed, we refer to Article III. Chapter XII.; and for the use and complete intelligence of the formulæ, we refer to each of the respective sections of the present chapter.

PRACTICAL FORMULÆ TO DETERMINE THE PROPORTIONS OF LOCOMOTIVE ENGINES, NECESSARY TO PRODUCE GIVEN EFFECTS.

$$(7) \ldots S = \frac{(1+\delta)v}{784}\left[(6 \pm g)M \pm gm + uv^2 + \frac{F}{1+\delta} + \frac{1}{1+\delta}\cdot\frac{d^2 l}{D}(2736 + p'v)\right]$$

...... Total vaporization of the boiler, in cubic feet of water per hour.

$$(8) \ldots d^2 = \frac{D}{l}\cdot\frac{1+\delta}{2736+p'v}\left[\frac{784}{1+\delta}\cdot\frac{S}{v} - (6 \pm g)M \mp gm - uv^2 - \frac{F}{1+\delta}\right] \ldots$$

...... Square of the diameter of the cylinder, in feet.

$$(9) \ldots l = \frac{D}{d^2}\cdot\frac{1+\delta}{2736+p'v}\left[\frac{784}{1+\delta}\cdot\frac{S}{v} - (6 \pm g)M \mp gm - uv^2 - \frac{F}{1+\delta}\right] \ldots$$

...... Stroke of the piston, in feet.

$$(10) \ldots D = \frac{d^2 l}{1+\delta}\cdot\frac{2736+p'v}{\frac{784}{1+\delta}\cdot\frac{S}{v} - (6 \pm g)M \mp gm - uv^2 - \frac{F}{1+\delta}} \ldots$$

...... Diameter of the wheel, in feet.

$$(11) \ldots S = \frac{1}{784}\cdot\frac{d^2 l}{D}\cdot v'(618 + P) \ldots$$

Total vaporization of the boiler, in cubic feet of water per hour.

$$(12) \ldots P = (1+\delta)\frac{D}{d^2 l}\left[(6 \pm g)M \pm gm + uv'^2 + \frac{F}{1+\delta}\right] + 2118 + p'v' \ldots$$

...... Total or absolute pressure of the steam in the boiler, in pounds per square foot.

$$(13) \ldots P = 784 \frac{D}{d^2 l} \cdot \frac{S}{v'} - 618$$ .... Total or absolute pressure of the steam in the boiler, in pounds per square foot.

$$(14) \ldots d^2 = 784 \frac{D}{l} \cdot \frac{S}{v'} \cdot \frac{1}{618 + P}$$ .... Square of the diameter of the cylinder, in feet.

$$(15) \ldots l = 784 \frac{D}{d^2} \cdot \frac{S}{v'} \cdot \frac{1}{618 + P}$$ .... Stroke of the piston, in feet.

$$(16) \ldots D = \frac{1}{784} \cdot d^2 l \cdot \frac{v'}{S} (618 + P)$$ .... Diameter of the wheel, in feet.

$$(17) \ldots d^2 = (1 + \delta) \frac{D}{l} \cdot \frac{(6 \pm g) M' \pm gm + uv'^2 + \frac{F}{1 + \delta}}{P - 2118 - p'v'}$$ .. Square of the diameter of the cylinder, in feet.

$$(18) \ldots l = (1 + \delta) \frac{D}{d^2} \cdot \frac{(6 \pm g) M' \pm gm + uv'^2 + \frac{F}{1 + \delta}}{P - 2118 - p'v'}$$ .. Stroke of the piston, in feet.

$$(19) \ldots D = \frac{d^2 l}{1 + \delta} \cdot \frac{P - 2118 - p'v'}{(6 \pm g) M' \pm gm + uv'^2 + \frac{F}{1 + \delta}}$$ .... Diameter of the wheel, in feet.

CHAPTER XIV.

OF ADHESION.

In the two preceding chapters, we have given the formulæ for calculating the effects or the proportions of the engines; but we must now speak of another condition without which the effects indicated could not be produced. This condition consists in the adhesion of the wheels to the rails being sufficient to effect the motion of the load.

It has been observed, in the description of the engine, that the effort of the steam being applied to the wheel, the engine is precisely in the case of a carriage which is made to advance by pushing at the spokes. Thus, as in this action the only fulcrum of the mover is the adhesion of the wheel to the rails, if that adhesion were insufficient, the force of the steam would indeed make the wheels turn; but these, sliding on the rails instead of adhering to them, would turn without advancing, and the engine would remain on the same spot.

The heavier the train to be drawn, the more force the engine must employ, and the more resistance it must consequently meet with at the point on which it strains to effect the motion. It might then

be feared that with trains of considerable weight, the engines would be unable to advance; not that force would be wanting in the mover itself, but in the fulcrum of the mover.

The experiments presented in Chapter XII. establish the measure of that adhesion in the fine weather season. In all these experiments, not one is found in which the motion was stopped or even slackened for want of adhesion. And yet we find among them loads amounting to above 300 tons.

If, for instance, we refer to the first experiment made with the FURY on the 24th July, and take account of the gravity in ascending the plane inclined $\frac{1}{98}$, we shall find that the engine then drew a load equivalent to 306 tons on a level. Since the engine advanced with this load, it follows that the adhesion was sufficient. Now the weight of the FURY is 8·20 tons, and that weight is so divided that 5·5 tons bear on the hind-wheels, which are the only propelling ones, the fore-wheels not serving at all to urge the engine forward, but merely to support it. It was then a weight of 5·5 tons that drew 306 tons, or a weight 55 times as considerable as itself; consequently, an engine having its four wheels coupled, and thus adhering by its whole weight, may draw a load equal to 55 times its own mass.

We have said that the engine FURY adheres but by two wheels. This disposition is general on the Liverpool Railway for all the trip engines, because

the adhesion of two wheels is sufficient for the loads they have to draw. As to the engines which serve as assistant engines on the inclined planes, they work with the adhesion of their four or six wheels, as has been said elsewhere. The engine Atlas is the only one employed for the trips, which differs from the others in this respect. This engine has six wheels, four of which, of equal size, are set in motion by the piston. The other two, smaller and without flange, may be raised out of contact with the rails by the action of the steam on a moveable piston. This disposition, which prevents these latter wheels from being inconvenient in turning, is due to Mr. John Melling, sen., of Liverpool.

To Mr. Melling also is due another very ingenious arrangement, by means of which an engine may be made to adhere by all its wheels, notwithstanding the difference of their diameters. It consists of a pulley, which is let down at pleasure between the two pairs of contiguous wheels, and which connects them so that one cannot turn without necessarily drawing the other with it. By means of this apparatus, engines may have their wheels unequal, which is very advantageous to the good arrangement of the machinery, and all their wheels need be put in communication only at the moment when that becomes necessary, which is done without stopping the engine.

We have just expressed the adhesion, by giving the measure of its effects; but that force itself may

be expressed in a direct manner. The load of 306 tons produced a resistance, or required a traction of 1836 lbs.; the adhesion was then equal to at least 1836 lbs., otherwise the wheel would have turned without going forward. Now the adhering weight was 5·5 tons, or, expressed in lbs., was 12,320 lbs.; it is plain then that the adhesive force was equal to about $\frac{1}{7}$ of the adhering weight. Considering that every 6 lbs. of force corresponds to the traction of 1 ton on a level, this expression amounts to the same as the first.

In winter, when the rails are greasy and dirty by the effect of wet weather, the adhesion diminishes considerably. However, unless in very extraordinary circumstances, the engines are always capable of drawing a load of 15 waggons or 75 tons, tender included, that is, 14 times their adhering weight; or, in other words, as the resistance of 75 tons is 450 lbs., the adhesive force is always at least $\frac{1}{27}$ of the adhering weight.

Adhesion being indispensable to the creation of the progressive motion, two conditions are requisite for an engine to be capable of drawing a given load: 1st, the dimensions and proportions of the engine and its boiler must enable it to produce, by means of the steam, the necessary pressure on the piston, which constitutes the force applied by the engine; and 2nd, the weight of the engine must be such as to cause a sufficient adhesion to the rails. These two conditions of force and weight should accord

together; for, were there a great force of steam and a slight adhesion, the latter would limit the effect of the engine, and steam would be lost; and were there too much adhesive weight for the power of the engine, that weight would, during the motion, become a useless burden, since the limit of the load would then be marked by the pressure of the steam.

It is necessary therefore, after having determined the dimensions of the engines from the conditions which they are to fulfil, as has been done in the preceding chapter, to seek what ought to be their weight so as to enable them to draw the greatest load intended to be imposed on them during their work. The enormous weight now given to locomotive engines, generally causes this condition to be fulfilled of itself. Six-wheel engines however require, in this respect, more attention than four-wheel engines, because it often happens, on an uneven railway, that a six-wheel engine is wholly supported on its four extreme wheels, whereas the middle ones, which are the propelling wheels, being accidentally situated immediately above a low part of the railway, scarcely touch the rail, and therefore have but a slight adhesion.

CHAPTER XV.

OF THE REGULATOR.

Sect. I. *Of the effects of the regulator on the velocity of the engine.*

It has been said, in the description of the different parts of the engine, that the pipe which brings the steam from the boiler to the cylinders may be closed, either entirely, or in part, by means of a cock or regulator, and that the velocity of the engine is regulated by this means. It becomes necessary then to consider how this effect is produced, and how the formulæ which we have given may keep account of it.

It is an opinion generally received, that by opening or shutting the regulator more or less, the pressure of the steam in the cylinder is augmented or diminished. But we have proved that the pressure in the cylinder is always strictly determined, *à priori*, by the resistance of the load against the piston. So long therefore as the load shall not vary, the pressure in the cylinder will not vary, and consequently the greater or less opening of the regulator can make no difference in it. Besides,

how could the contraction of a passage change the *pressure* of a gas or steam issuing through that passage? It may indeed change its *quantity*, because the smallness of the aperture prevents more than a certain volume from passing in a given time; but unquestionably it can never change the pressure, for it will always happen that as soon as the steam, having got through the passage, shall arrive in the cylinder, and shall there acquire the pressure of the resistance, the piston will recede without allowing it to assume a higher pressure. And if it be supposed that by enlarging the passage, the steam may be made to come ten or twenty times quicker, the piston will recede ten times or twenty times quicker also, since its motion is the result of the arrival of the steam; but the pressure in the cylinder can never exceed the resistance of the piston, because the piston being nothing more nor less than a valve to the cylinder, it would be supposing a boiler in which the pressure of the steam should be greater than that of the safety-valve.

Thus the narrowing of the regulator cannot diminish the pressure of the steam in the cylinder. Moreover, a diminution of pressure in the cylinder would not account for the diminution of velocity of the engine, which is observed when the regulator is partially closed; except indeed the motion should be attributed, as it has been by some, to an excess of the pressure of the steam in the cylinder above the resistance of the piston. But this opinion

would be altogether an error; for if such excess existed, the motion of the engine would not be uniform, but indefinitely accelerated. On the contrary, the pressure of the steam is equal to the resistance of the piston, and the motion is owing to the velocity with which the steam arrives, at that pressure. Hence, the above-mentioned suppositions are inadmissible. But the effects of the regulator are easily accounted for in another manner.

The quantity of steam of a given density, which issues forth through a determined orifice, being in the ratio of the area of that orifice, it follows that if we lessen the orifice of the regulator, we shall thereby diminish the *quantity* of steam, at the pressure of the boiler, which can issue by the orifice of the regulator to pass into the cylinders. If however the fire be kept up at the same degree of intensity, it will continue to produce the same quantity of steam per minute. This steam, which can no longer flow in totality towards the cylinder, will therefore accumulate in the boiler, and there rise to a still greater and greater density and elastic force, till at last it be able to find some outlet.

Now the steam has two outlets whereby to escape from the boiler, namely: the passage of the regulator, which, notwithstanding its contraction, would admit of the total efflux of the steam, as it is generated, if that steam acquired a sufficient degree of *density*, or, in other words, a volume sufficiently small for that effect; and the safety-valve, which

would equally admit of its escape, were the steam to acquire a *pressure* sufficient to raise the valve. Two cases then will occur, according as the steam, continuing to accumulate in the boiler, shall acquire more promptly either the pressure which admits of its issue by the safety-valve, or the density which enables it to flow out entirely by the regulator.

1st. If the regulator is much contracted, and if the safety-valve of the boiler, on the contrary, is fixed at a moderate pressure, the steam retained in the boiler will soon attain the degree necessary to raise the safety-valve. The valve then will be open, and all the surplus steam generated in the boiler, beyond what can issue by the regulator, will escape into the atmosphere; and this effect will continue so long as nothing shall be changed in the engine, because there will still be the same necessity for the steam to effect its efflux as it is generated, and because the resistance of the obstacles which it has to overcome will remain still the same.

Thus, the effect of the contraction of the regulator will be, to cause a portion more or less of the steam produced by the boiler to be lost in the atmosphere; and as the effects of the engine are attributable only to the *effective* vaporization, that is to say, to the portion of the total steam which really penetrates into the cylinders, it follows that the velocity of the engine will be reduced precisely in proportion to the quantity of steam lost. Hence, the effect of the contraction of the regulator will be to reduce

the velocity of the engine immediately. Then, after the first few moments of the contraction of the regulator, the engineer seeing a considerable quantity of steam running to waste by the safety-valve, will naturally cease to keep up his fire with the same activity. The vaporization produced in the boiler will be diminished in consequence; and by continual reduction of the fire there will at last be no more steam generated than may effectively penetrate into the cylinders. From this moment then the blowing of the safety-valve will cease, and the velocity of the engine will continue as it was regulated at first by the contraction of the regulator.

Consequently it is manifest that the regulator diminishes the velocity of the engine, by immediately reducing the effective vaporization, and ulteriorly the total vaporization of the boiler; and it is also manifest that its effect is not to diminish the pressure in the cylinder, but to augment the pressure in the boiler.

2nd. We have just supposed the case wherein the regulator is sufficiently contracted to make the safety-valve blow, and have seen what effects will result therefrom. But another case may occur, namely: that in which the regulator should also be contracted, but yet not sufficiently so to make the safety-valve blow; that is to say, the case wherein the steam, accumulating in the boiler, should attain the density which permits its total efflux by the regulator, before it attains the pressure necessary to raise the safety-valve. Then, since the valve

does not blow, and no portion of the steam produced is lost, it is clear that all the steam will pass into the cylinder and act there as before. Hence the velocity of the engine will in nowise be changed; for that velocity cannot be augmented nor diminished except by an increase or a reduction of the effective vaporization of the engine, and this circumstance does not occur in the case supposed.

Notwithstanding, therefore, the contraction of the regulator, the velocity of the engine will remain the same, and there will result, as in the preceding case, only an increase of pressure in the boiler.

From these considerations, we see that the unique and immediate effect of the contraction of the regulator is to augment the pressure of the steam in the boiler; and that if the increase of pressure is such as to cause a loss of steam by the safety-valve, the velocity of the engine will be reduced precisely in the same proportion, but that if no such loss takes place, the velocity undergoes no reduction.

Now, in the formulæ which we have given to calculate the velocity of the engines, the quantity S represents the *effective* vaporization of the engine, that is to say, the quantity of water which, being converted to steam, really penetrates into the cylinders and acts upon the piston. If, notwithstanding the contraction of the regulator, there is no loss of steam by the safety-valve, the effective vaporization of the engine will not be changed, that is, the quantity S will remain the same, and consequently the formulæ will still continue to give the same

result for the velocity of the engine. On the other hand, if a loss of steam takes place by the safety-valve, that loss must obviously be subtracted from the total vaporization of the boiler, in order to deduce from it the effective vaporization, or the quantity which ought to be substituted for S in the equations, and then the result of those formulæ will be reduced in a proportionate quantity. In either case, therefore, the formulæ which we have given will always continue to make known the true effects produced by the engine. All they require is, that account be taken of the loss by the valves, when that loss occurs, and we have already shown in Chapter X. how it may be estimated.

These considerations will be found confirmed by the experiments presented in Chapter XII. It will there be observed that the formulæ give results quite as exact for the case wherein the regulator was partially closed, as for the case in which it was entirely open. And the reason is this, that when the partial close of the regulator was attended with a loss by the valve, we took account of it in the value of the effective vaporization S, by taking that value equal to the total vaporization of the engine, diminished by the loss at the valves.

Sect. II. *Dimensions of the steam-passages in some locomotive engines.*

We will close this chapter by giving the diameter of the steam-pipes in the engines which we submitted to experiment, and in some others whose

dimensions have been given at the beginning of this work. The pipes here considered are those which lead separately from the boiler to each slide-box. Those which afterwards lead from that box to the cylinders, are of a corresponding surface, though of a different shape. For instance, when they form the continuation of a tube 3 inches in diameter, they are made 7 inches long by 1 inch wide, which presents the same surface for the passage of the steam.

It will be remarked that the steam-passages are much wider in locomotive engines than in stationary steam engines, since in these the area of the steam-passage is but $\frac{1}{25}$ of the area of the cylinder, while in locomotive engines the proportion between the same parts is in general $\frac{1}{12}$.

Steam-pipes in some of the locomotive engines of the Liverpool and Manchester Railway.

Name of the engine.	Diameter of the cylinder.	Stroke of the piston.	Heating surface of the fire-box.	Heating surface of the tubes.	Inner diameter of the steam-pipes.
	inches.	inches.	sq. feet.	sq. feet.	inches.
Samson.	14	16	40·20	377·41	3·25
Goliath I.	14	16	40·31	355·84	3·25
Atlas.	12	16	57·06	197·25	3·25
Vulcan.	11	16	34·45	267·84	3·50
Fury.	11	16	32·87	267·84	3·50
Vesta.	$11\frac{1}{8}$	16	46·00	215·66	3·25
Leeds.	11	16	34·57	267·84	3·50
Firefly I.	11	18	43·91	317·71	3·00
Star.	14	12	49·71	279·18	3·75

CHAPTER XVI.

OF THE LEAD OF THE SLIDE.

SECT. I. *Of the nature and effects of the lead of the slide.*

WE have said, in describing the different parts of the engine, that it is the slide which successively opens and shuts the steam-ports above and below the piston, so as to apply the effort of the steam alternately on each side. Were the engine regulated as it might seem natural to regulate it, the slide would keep the steam-port open till the piston arrived at the bottom of the cylinder. At this moment it would change: the first passage would be closed, and the opposite one opened. Then the motion of the slide would exactly accompany that of the piston, that is to say, their alternations would be strictly simultaneous.

But the thing is not so ordered. At the moment when the piston is about to terminate its stroke, it is needless and even detrimental to the engine to apply any new impulsion on it, since it is then at the moment of stopping, to perform its retrograde stroke. Besides, it is proper to allow the steam,

which now fills the cylinder, time to escape as much as possible, before the piston is brought back in a contrary direction, since it would otherwise contribute to form an obstacle, on account of the smallness of the orifice of the blast-pipe; and finally, rather than let the piston strike against the end of the cylinder, or exert at least an effort in that direction against the crank of the axle, it is preferable to present to it an elastic body which may deaden its shock. With this threefold purpose, then, the motion of the slide is regulated in such sort, that successively, and before the piston reaches the end of the cylinder, the three following operations are performed: 1st, the communication is intercepted between the boiler and the steam-port through which the steam is actually coming, which suspends all addition to the motive force; 2dly, the communication of the same port with the waste steam-port is opened, which permits the escape of the steam by anticipation, while it still continues its action; 3rdly, the communication between the boiler and the steam-port which conducts the steam upon the piston, in a contrary way to its motion, is opened; which deadens the shock of the piston, relieves the joints of the machinery, and enables the steam to act with full force on the piston, as soon as the latter begins its retrograde stroke. These three successive operations, as we have said, are performed before the piston reaches the bottom of the cylinder, and, by means of divers

dispositions, they may be so regulated as to take place on points more or less anterior to the end of the stroke.

When the engine is regulated as we have just explained, it is visible that at the moment when the piston terminates its stroke to begin another, the slide has already, for a certain space of time, been intercepting the coming of the steam in favour of the motion, and has even already admitted it in the contrary direction during another interval of time less than the former; or, in other words, the slide has already traversed a certain space in the direction of its stroke, from the moment when it closed the first passage, and another space less than the former, from the moment when it opened the contrary passage. It is this anticipation of the motion of the slide upon that of the piston which is called *the lead of the slide*, because it indicates by how much the motion of the slide precedes that of the piston; but it is conceivable, from what has been said, that a distinction is to be made between the lead of the slide for the *suppression* of the steam, and the lead of the slide for the *admission* of the steam, though the latter is more particularly understood when it is simply said the lead of the slide. These two sorts of lead are sometimes distinguished by saying the lead on the exhausting side and the lead on the boiler side, but the former mode appears to us to be more exact.

When the slide valve is single, that is to say, con-

sisting of a single box, like that of fig. 26 (Pl. IV.), the difference between the two leads is equal to twice the overlap of the slide. In effect, on examining that figure, which represents the slide at the moment when it changes the passages of the steam, and supposing its motion to have been in the direction of the arrow, it will be recognised that as soon as the slide arrives at the position *a*, the coming of the steam is intercepted in the left-hand passage, but that the right-hand passage does not begin to open till the slide attains the position *c*. If then we suppose the passage still more opened, and the slide arrived at the position *d* at the same time that the piston reaches the bottom of the cylinder, it is plain that the quantity *c d* by which the passage is then open, will be what we call the lead of the slide for the admission of the steam; but that the opposite passage will have been shut, and consequently the motive force, in the direction of the motion, will have been intercepted from the point *a*, that is to say, the lead for the suppression of the steam will necessarily be equal to the lead of admission augmented by twice the overlap of the slide. When the slide is double, or composed of two boxes which may be set further apart or nearer to each other at pleasure by means of an adjusting screw, each lead may be regulated separately at the point which may be judged suitable, and this is an advantage, but the slide is more liable to get out of order.

As the disposition of the slide, which has just been described, has the result of suppressing the

motive force, at a certain point of the stroke of the piston, to introduce it afterwards in the contrary direction, it is evident that its effect on the engine cannot be calculated till after an exact determination of that point of the cylinder, at which the piston is at the moment when the close and the opening of the respective passages take place. This is therefore the first inquiry that will occupy our attention.

With this view, we return to the single slide valve represented in figs. 10 and 26. On examining these two figures, it will be perceived that if the radius of the eccentric were strictly at right angles with the radius of the crank, it would then so happen that the slide would be in its middle position, indicated by the figure, precisely at the moment when the piston should arrive at the end of its stroke. In this case, the suppression of the steam in favour of the motion would take place, before this point, by a distance equal to the overlap of the slide on the two ports; and the admission of the steam by the opposite passage would take place, after that same point, by a distance equal to the same overlap. But if it be wished to give the engine a certain lead of the slide for the admission of the steam, the passage of the steam opposed to the present motion of the piston must be already open a certain quantity, at the moment when the piston terminates its stroke. To this end, therefore, the radius of the eccentric must incline forward, from the perpendicular to the radius of the crank,

in an angle corresponding to the lead in question augmented by the overlap of the slide. In effect, if it be thus, we see that when the radius of the crank coincides with the horizontal line, that is to say, when the piston is at the end of its stroke, the radius of the eccentric has passed the vertical by a quantity corresponding to the lead of admission plus the overlap; that is to say, the slide has passed its middle position, just the quantity necessary to open the steam-port the quantity indicated by the lead.

This premised, suppose $b\,D'$ (fig. 27) to represent the radius of the crank, and bb' the radius of the eccentric. When the radius of the eccentric coincides with the vertical, the slide is in its middle position and all the passages are closed. After it has passed this point a quantity equal to the overlap, the passage of the steam opposed to the motion of the piston will begin to open, and when the radius of the eccentric shall have reached bd', the slide will open that passage the quantity indicated by the lead. But since the eccentric and the crank turn in one piece with the axle of the engine, it follows that their radii describe equal angles in the same time. Hence, while the radius of the eccentric describes the angle $b'bd'$, the radius of the crank describes an angle $D'bB$ equal to the former. On the other hand, while the eccentric describes the angle $b'bd'$, the slide, which moves horizontally, traverses the space bd, which is equal to $d'p$; that is to say, it traverses the sine of the angle $b'bd'$, in

a circle whose radius is equal to that of the eccentric. Similarly, while the crank describes the angle $D'bB$, the piston traverses the space DB, that is, the versed sine of the angle described, in a circle whose radius is equal to that of the crank.

Finally therefore, while the slide, departing from its middle position, performs the sines of the angles, in the circle of the eccentric, the piston, to finish its stroke, performs the versed sines of the same angles, in the circle of the crank. Consequently it will be easy to find the correlative situations of those two pieces. It will suffice for this purpose, in practice, to draw exactly and by the scale the figure 27, in which bs is the radius of the eccentric or the half range of the slide, bB the radius of the crank or the half stroke of the piston, and db the distance at which the slide is supposed to be from its middle position. Then, raising at the point d, the perpendicular dd', we have the point d'; afterwards taking the angle BbD' equal to the angle $b'bd'$, we determine the point D', and finally, letting fall the perpendicular $D'D$, we have definitively the distance DB, between the point D, where the piston then is, and the point B which is the end of its stroke.

If it be desired to find the quantity DB by calculation, it will suffice, from what has just been said, to consider the given distance db as the sine of an angle, and to seek the corresponding versed sine. Therefore, the ratio of the line db, to the radius bs,

of the circle in which that line is drawn, must be found; which is easy, since those two lines are known. Then the logarithm of that ratio must be taken, and that logarithm sought in the column of sines of a Table of ordinary sines. Close to this will be found the logarithm of the corresponding cosine, and consequently on seeking the number which that logarithm represents, the cosine of the angle described will be known. Subtracting this cosine from unity, the difference will be the versed sine of the same angle. This will then be the ratio between the line DB and the radius *b*B of the circle in which that line is drawn. Consequently, as the line *b*B is known, it will be easy to determine from it the absolute measure of DB the line sought.

If we take for example an engine in which the stroke of the piston is 16 inches, range of the slide 3 inches, overlap of the slide over the steam-ways $\frac{1}{8}$ inch; and if we suppose the engine to have a lead of admission of $\frac{5}{8}$ inch, and a lead of suppression of $\frac{7}{8}$ inch; and it be required to find at what distance from the end of the cylinder the piston is when the steam is intercepted, and at what point it is when the steam is introduced against it, we shall find by following the calculation indicated above, and applying it successively to the two given distances, that the space remaining for the piston to traverse at the moment the steam is intercepted in favour of the motion, is 1·50 inch; and that when the steam

is introduced in the opposite direction, the piston is ·73 inch from the end of its stroke. The figure 27, constructed by the scale, gives the same result.

If we suppose in the same engine a lead of $\frac{1}{8}$ and $\frac{3}{8}$ inch in each respective direction, we find by a similar calculation, that the space remaining for the piston to traverse when the arrival of the steam is intercepted in the direction of the motion, is ·25 inch, and that the steam is introduced in the opposite direction when the piston is ·03 inch from the end of its stroke.

These examples show how, when the lead is given, or when the situation of the slide is known at any moment whatever, the point at which the piston is at the same moment may always be deduced from it.

SECT. II. *Of the effects of the lead of the slide on the velocity of the engine.*

We have already mentioned the advantages arising from the lead of the slide, with regard to the play and the conservation of the engine; but there is another advantage no less important, resulting from this disposition, namely, that of obtaining a greater velocity, and consequently a greater useful effect of the engine with a given load.

This effect is easy to comprehend; for if the suppression of the steam from the boiler, instead of being made precisely at the end of the stroke of the

piston, takes place, for instance, at the moment when the piston is yet an inch from the bottom of the cylinder, from that moment steam ceases to flow into the cylinder. Thus, with regard to the quantity of steam admitted into the cylinder or expended at each stroke of the piston, the length of the stroke is really diminished an inch. Now it is the quantity of steam produced by the boiler which regulates and limits the velocity of the engine. Suppose that such production furnished m cylinders-full of steam per minute, when the total length l of the stroke was filled with steam: now no more than the length $l-\alpha$ is filled with steam; the same production then will fill per minute a number of cylinders expressed by $m \times \frac{l}{l-\alpha}$. Hence, in fine, the velocity of the engine will be increased in the inverse ratio of the lengths of the cylinder which are filled with steam.

It is to be observed, indeed, that while a lead is given to the slide, to suppress the steam coming from the boiler, a lead is also given to admit the steam against the piston, before the latter has reached the bottom of the cylinder. There results then an increase in the mean resistance opposed to the motion of the piston during the whole of the stroke; and since the velocity of the engine decreases as the resistance which it has to overcome becomes greater, it might be deemed that this circumstance compensates for the former. But as, by

means of double slide valve boxes, it is possible to have a considerable lead for the suppression of the steam, and a very small one for the admission of the steam in the contrary direction, and as, even with single slide valves, the steam is never admitted against the piston but when the latter is at a very small distance from the end of the stroke, and consequently at a point where a great force could produce but a very small effort against the motion of the crank of the axle, it will be recognised that this circumstance will not sensibly retard the progress of the engine. It may then be generally admitted that the velocity of the engine will increase in the ratio of the total stroke of the piston, to the portion traversed at the moment of the suppression of the steam by the effect of the slide.

This premised, it is visible, from the calculation which we have given in the preceding section, that when the lead of the slide for the suppression of the steam is but $\frac{3}{8}$ inch, on a total range of 3 inches, the increase of the velocity of the engine must be inconsiderable, since the steam is then suppressed on ·25 inch only, or on $\frac{1}{64}$ of the total stroke of the piston. If the lead of suppression amount to $\frac{4}{8}$ or $\frac{5}{8}$ inch, it produces a more sensible effect, which nevertheless may easily be compensated by the strength of the wind, by care in maintaining the fire, or by the quality of the fuel; but if it amount to $\frac{7}{8}$ inch, calculation shows that it may produce an augmentation of about two miles on a velocity

of thirty miles per hour; and in this case as well as in those in which the lead is greater still, it is conceivable that its effects must manifest themselves in practice.

Among all the engines employed in the experiments presented in Chapter XII., there was not one, except the VESTA which we shall presently notice, in which the lead of the slide was in the case last mentioned, that is, in which the lead of the slide could have any very sensible effect on the velocity. It is besides to be observed that when, in Chapter X., we determined the *effective* vaporization of the engines, or the loss of water carried with the steam in a liquid state, we did, in fact, take account of the lead of the slide for each engine. In effect, since the engine had then a lead of the slide, we ought to have calculated the cylinder-full, not by the entire stroke of the piston as we did, but by the stroke after deducting the portion corresponding to the slide; that is to say, retaining the notations just employed above, by the length $l - a$. But then the velocity of the engine, corresponding to the real vaporization of all the water consumed by the boiler, would have been increased in the ratio $\frac{l}{l - a}$; and in consequence the *effective* vaporization would have been diminished in the ratio $\frac{l - a}{l}$. The calculation performed with this new *effective* vaporization, would then have given for the engine

a velocity less in the same ratio; and in fine, to take account of the lead of the slide, it would have been necessary to multiply that velocity by the ratio $\frac{l}{l - a}$. Hence we should thus have fallen back on the same velocity which we obtained more simply by the method followed; and for this reason, considering besides how small the lead was, in the engines submitted to experiment, we preferred not to let those details figure in the calculation.

In the experiments of Chapter XII., and in all the calculations of velocity made from our determinations, on engines having but little lead of the slide, it becomes needless then to enter into the consideration of the lead. But the engine VESTA, as we have said above, forms an exception in this respect. In effect, there existed in that engine a peculiar disposition which admitted of changing the lead of the slide at pleasure; and while the engine was ascending the inclined plane of *Whiston*, which was the moment when its effective vaporization was calculated, the lead of the slide for the suppression of the steam had been reduced to $\frac{5}{8}$ inch, whereas during the rest of the trip that lead had been fixed at $\frac{11}{8}$ inch. The *effective* vaporization of the engine is then determined as comprehending a lead of only $\frac{5}{8}$ inch instead of $\frac{11}{8}$ inch; and as the former of these two leads reduces the stroke of the piston 1·50 inch, while the latter reduces it 3·35 inches, it becomes necessary, in order to take account of this difference,

to calculate the velocities of that engine by taking the effective stroke of the piston at 12·65 inches, instead of 14·50 inches, as it was with the lead of $\frac{5}{8}$ inch. This we did in calculating the velocities of that engine, and had we not had regard to this circumstance, the calculation would have given about 3 miles less on each of the velocities of the engine.

From what has just been seen, the lead of the slide augments the velocity of the engine with a given load, and consequently its useful effect with that load. Therefore, as the lead of the slide shall be augmented, the useful effect will augment at the same time, and this augmentation will continue till, by reason of the lead, the effective stroke of the piston is so much reduced, that the given load becomes a *maximum* load for the engine with that stroke. Reckoning from this point, the lead of the slide, and consequently the useful effect of the engine with the given load, admit of no further augmentation, since any further increase of the lead, or, in other words, any further diminution of the effective stroke of the piston, would render the engine incapable of drawing the desired load.

Sect. III. *Of the effects of the lead of the slide on the maximum load of which the engine is capable.*

The advantages of the lead of the slide, which we have just noticed, are very important, since they consist in augmenting the velocity of the engine

with a given load, or, in other words, its useful effect for a given vaporization, which implies the diminishing of its consumption of fuel for determined effects. These advantages are produced in the inverse proportion of the lengths of the cylinder which are filled with steam at each stroke of the piston, and are therefore perfectly analogous to those which would result in the engine from an actual diminution of the stroke of the piston. But they are attended with a disadvantage which it is necessary to notice here, and which would equally occur in the case of an actual diminution of the stroke of the piston. The disadvantage consists in this, that the *maximum* load which the engine is capable of drawing becomes less at the same time; so that, for the producing of certain effects, it may be advantageous to diminish, or even altogether to suppress, the lead of the slide.

To be convinced of this fact, it suffices to observe that at the moment when the piston reaches the point which corresponds to the lead of the slide for the suppression of the steam, the motive force is suppressed; and that, when the piston, continuing its stroke in virtue of its acquired velocity, arrives at the point which corresponds to the lead for the admission of the steam, it not only receives no further impulse in the direction of the motion, but suffers an opposition from the motive force itself, then let in against it. Now the piston cannot stop; it must finish its stroke. It is therefore obliged to

drive back the new steam which obstructs its way; and as it consumes in overcoming the obstacle a quantity of work equal to that which this steam would have communicated to it, it follows that through the space yet remaining to traverse, there is destruction of the force previously acquired on an equal length of the cylinder. Thus, representing by α and β the two portions of the stroke of the piston, which correspond to the two leads for the suppression and admission of the steam, we see that the effect of the motive force, for the definitive motion, is now produced only on the length of the stroke, diminished first by α and afterwards by β, or that there really remains, for the effort exerted by the engine, a stroke equal only to $l - \alpha - \beta$.

It will be remarked, indeed, that at the moment the steam is intercepted and the waste steam-port open, the motive force of the motion is not suppressed instantaneously, and that on the opening of the opposite port, the motive force is not let in instantaneously in the opposite direction; for, as the steam requires a certain material time, either to escape from above the piston, or to penetrate on the opposite side of it, it follows that during its efflux by the blast-pipe, that steam does not entirely cease to exert an effort on the piston; neither, during its admission against the motion of the piston, has it, from the first, all the pressure of which it is capable to resist it. Moreover, during this suppression of the motive force in one direction and its introduction in

the other, it will be remarked that the piston is very near the end of the cylinder, which occasions its action on the crank, that is, its action to produce or retard the motion of the engine, to be nearly null. From these two circumstances then it results, that the loss of motive force on the length α of the stroke of the piston, and its introduction in the opposite direction on the length β of the same stroke, are but partial; but calculating approximatively, the effects of the engine may nevertheless be computed in supposing the effective stroke reduced to the length $l-\alpha-\beta$.

Now, referring to the expression of the *maximum* load that the engine can draw (Chap. XII. Art. II. Sect. II.), we recognise that the more the quantity l diminishes, that is, the shorter the stroke of the piston becomes, the more the corresponding value of the load diminishes. Moreover, while the motive force is exerted only on the length $l-\alpha-\beta$, the resistance of the load continues nevertheless to be exerted on the total length l of the stroke. From this fact then results a new disadvantage to the power, that is to say, a new diminution of the maximum load; and consequently, by these two causes, the extreme load of which the engine is capable will be by so much the less as the lead of the slide is greater.

To recognise by direct experiment to what degree the maximum load of an engine may be diminished by the lead of the slide, we undertook a series of experiments on the subject with the engine VESTA.

By a peculiar disposition, due to Mr. J. Gray, one of the engine-builders of the Liverpool and Manchester Railway Company, this engine could, without interrupting its progress, be regulated for different leads of the slide, so that, with the same load and on the same ground, the effect of those different changes might be tried. They were produced by means of three notches, more or less advanced on the eccentric, and on which the driver might be brought at pleasure by means of a lever. The total range of the slide was 3·38 inches, and the three notches gave the following leads of the slide:

1st notch	lead of suppression . . .	$\frac{5}{8}$ inch.
	lead of admission	$\frac{1}{8}$
2nd notch	lead of suppression . . .	$\frac{8}{8}$
	lead of admission	$\frac{2}{8}$
3rd notch	lead of suppression . . .	$\frac{11}{8}$
	lead of admission	$\frac{5}{8}$

To render the differences more sensible, it was between the first and the third of these positions of the slide that we endeavoured to obtain a comparison. Consequently, on the 16th August, 1834, in the morning, and on the same day in the evening, the engine having been brought to the foot of the inclined plane of *Whiston*, inclined $\frac{1}{89}$, first with a train of 20 waggons, and afterwards with a train of 8 waggons, every one of which had been previously weighed, a number more or less of these waggons was detached successively, and with each of these loads the greater and the lesser lead were successively tried. The results of these trials are presented in the following Table.

Experiments on the effects of the lead of the slide, on the load of locomotive engines.

Name and designation of the engine.	Number of the experiment.	Load of the engine, tender included.	Leads of the slide, $\frac{11}{8}$ and $\frac{5}{8}$ inch. Velocity, in complete strokes of the piston per minute.	Leads of the slide, $\frac{11}{8}$ and $\frac{5}{8}$ inch. Effective pressure, in lbs. per sq. inch.	Leads of the slide, $\frac{5}{8}$ and $\frac{1}{8}$ inch. Velocity, in complete strokes of the piston per minute.	Leads of the slide, $\frac{5}{8}$ and $\frac{1}{8}$ inch. Effective pressure, in lbs. per sq. inch.
		tons.		lbs.		lbs.
VESTA, cylinders . . . $11\frac{1}{8}$ in.	I.	48·18	The engine stops	56·5	Stops	56·5
stroke of the piston 16 in.	II.	39·93	Stops	58	Starts and gives 14 s. per min.	57·25
wheel . . . . 5 ft.	III.	39·05	Stops	56·5	Starts and gives 17 s. per min.	56·5
weight . . . 8·71 tons.	IV.	35·38	Stops	56·5	Starts	56·5
friction . . . 181 lbs.	V.	33·55	Stops	56·5	Starts	52
range of the slide 3·38 in.	VI.	32·05	Gives 46 s. of pist. per min.	56·5		

From these experiments it appears, that all the engine could do, with the leads of $\frac{11}{8}$ and $\frac{5}{8}$ inch, was to draw a load weighing 32·05 tons; and that with the leads of $\frac{5}{8}$ and $\frac{1}{8}$ inch it could, with the same pressure in the boiler, draw a load of 39·05 tons. Taking into the account the gravity of the train and engine on the plane inclined $\frac{1}{89}$, these two loads are equivalent to 212 and 248 tons on a level. Thus the maximum load of the engine was reduced, by the lead, about $\frac{1}{6}$, which may become important under certain circumstances.

Sect. IV. *Of the manner of regulating the lead of the slide.*

The preceding researches make known the effects of the lead of the slide, either on the velocity, or on the maximum load of the engine. We are then to be guided in this respect by the effects that are desired to be obtained from the engine.

It is besides an easy thing to know the lead of the slide, and to regulate it at the point that may be thought proper.

After having opened the door of the smoke-box situated under the chimney, and taken off the top of the slide valve box, so as to uncover the slides and observe their motion, the engine must be gently pushed forward on the rails, by hand, till the crank of the axle lies perfectly horizontal.

At this moment the piston is at the end of the

cylinder. Measuring then the quantity by which the slide now opens the steam-port, we have the lead of the slide.

If it be desired to change the lead, the crank must be retained in the same position, and detaching the driver which is fixed to the axle only by a stop screw, the eccentric must be turned by hand till the slide, which moves at the same time, shall have opened the steam-port the desired quantity. Then the driver is to be refixed so as to hold the eccentric in that position. This operation being ended, it is plain that every time the crank shall lie horizontally or the piston be ready to begin its stroke, the slide will be found to open the steam-port the proper quantity.

We have said, that to bring the crank horizontal, it is in the forward direction that the engine must be pushed. The motive of this distinction is, that all the joints be tightened in the same manner as they are in the progressive motion of the engine. It is necessary also to bear in mind that these joints will be still more tightened, and the lead of the slide somewhat reduced, when the engine has to sustain the tension produced by a considerable load.

Another attention is necessary before giving the lead, or measuring it, and this is to ascertain that the slide has an equal play between the three ports of the cylinder; that is to say, that in its two extreme positions it is equally distant from the two

sides of the middle or waste steam-port. Otherwise the lead of the slide would not be equal in the two motions of the piston. This defect, if it exist, is easily corrected by lengthening or shortening the eccentric rod as may be required. This rod is purposely formed of two parts (figs. 9 and 10), terminated by a right and left screw, and joined by an adjusting-box E. When the box is turned, for instance, to the right, the two screws tighten and the rod shortens. If on the contrary it is turned to the left, the two screws become less tight and the rod lengthens.

The regulation of the slide then is an easy operation.

The lead of the slide may, moreover, be changed with tolerable exactitude without opening the engine. It suffices to make beforehand on the axle, with a chisel and a hammer, two or three notches corresponding to two or three positions of the driver for given leads. These marks being once carefully determined as above, it is easy, by advancing the driver from one to the other, to make the slide pass from one lead to another greater or less. This is the means which we employed in some essays which we first made on this subject with the engine Leeds, and in which we successively changed the lead, from nil to $\frac{1}{8}$ and $\frac{2}{8}$ inch.

The engine-men have several approximative ways of attaining the same end. They have remarked that, in general, a variation of $\frac{1}{2}$ inch for the driver

in the opening of the eccentric, corresponds to a variation of $\frac{1}{8}$ inch in the lead of the slide. Thus, knowing the actual lead of the engine, they may, guided by this observation, diminish or augment that lead as much as they think proper. They attain their end also by loosening some keys or joints, so that the eccentric-rod no longer draws the rod of the slides immediately after it, but leaves, for instance, $\frac{1}{8}$ inch of play in the communication of the motion from the one to the other. It is readily conceived that, by this means, the slide will begin its motion $\frac{1}{8}$ inch after the eccentric. If then the slide had before a lead of $\frac{3}{8}$ inch, its lead afterwards will be but $\frac{2}{8}$ inch. But this means and other similar ones are detrimental to the engine.

CHAPTER XVII.

OF INCLINED PLANES.

SECT. I. *Of the load on a level, which corresponds to the load on a given inclined plane, and vice versâ.*

WE have already shown, in Chapter VI., the means of computing the resistance opposed to the motion of the engines, by the gravity of the trains placed on inclined planes; but as many other questions occur relative to inclined planes on railways, we must here return to the subject, to solve the problems which arise out of them.

It often happens that an engine is observed to draw a certain load on a certain inclination, and to compare this work with that of another engine which would perform another task on a different inclination, it becomes necessary to refer each of these loads to the *level*. We shall therefore begin with this problem; that is to say, we shall seek the means of passing from a given load, drawn on a known inclination, to a train which would offer an equal resistance on a level; and reciprocally, from a known train, drawn on a level,

to the load which, on a given inclination, would offer an equal resistance.

1stly. Let us take the first case, and suppose the practical inclination of the plane to be expressed by $\frac{1}{e}$, that is to say, suppose its vertical elevation to be to its length measured along the plane, in the ratio of $\frac{1}{e}$. Let M be the weight, in tons gross, tender included, of the train placed on this inclined plane; and let k be the friction of the waggons per ton, expressed in pounds, as has been explained Chapter V. Finally, let m be the weight, expressed in tons, of the engine which performs the traction.

With these notations, it is clear that $k\mathrm{M}$ will be the friction of the carriages of the train. Moreover, since 1 ton contains 2240 lbs., the gravity of the train, plus the engine, will, as has been shown, Chapter VI., be expressed by

$$2240\,\frac{\mathrm{M}+m}{e}.$$

Consequently, according as the engine has to ascend or to descend the plane, the total resistance it meets with from the train will be

$$k\mathrm{M} \pm 2240\,\frac{\mathrm{M}+m}{e}.$$

Therefore the train which, on a level, would offer an equivalent resistance, will have for its expression, when the motion is ascending,

$$M'' = M + \frac{2240}{k} \cdot \frac{M+m}{e};$$

and when it is descending,

$$M'' = M - \frac{2240}{k} \cdot \frac{M+m}{e}.$$

If, for instance, there be a load of 50 tons, tender included, drawn up a plane inclined $\frac{1}{800}$, by an engine of the weight of 8 tons, it will be found that the equivalent load on a level will be 86 tons; and if the traction takes place in descending, the equivalent load on a level will be no more than 14 tons.

The case of descending trains offers no more difficulty than that of ascending ones; but it is to be remarked that when

$$M = \frac{2240}{k} \cdot \frac{M+m}{e},$$

that is to say, when the train descends a plane whose inclination is expressed by

$$\frac{1}{e} = \frac{k}{2240} \cdot \frac{M}{M+m},$$

the load which represents the resistance of the train will become null. Thus, on the plane whose inclination we have just found, the friction proper to the waggons will be exactly counterbalanced by the gravity of the train augmented by that of the engine. On any plane of greater inclination, the resistance offered by the train, or the load M″, will be found negative; that is to say, that so far

from opposing the progress of the engine, the waggons will tend on the contrary to urge it along the plane, with a force represented by the negative value thus obtained.

When therefore the inclination of the plane, the weight of the waggons and that of the engine are known, the load M″, which would offer an equivalent resistance on a level, may immediately be found.

2ndly. Suppose now that the result of an experiment have made known the load M″ which a given engine can draw upon a level, and that it be desired to deduce therefrom the load M which the same engine could draw on a plane of a given inclination; then the preceding equation, resolved with reference to M, will give, when the motion is ascending,

$$M = \frac{ek\,M'' - 2240\,m}{ek + 2240};$$

and when it is descending,

$$M = \frac{ek\,M'' + 2240\,m}{ek - 2240}.$$

It will be easy then to find the load M required.

If, for instance, we had found 86 tons for the load of an engine on a level, it would be deduced from thence that, on a plane ascending $\frac{1}{600}$, and for an engine of the weight of 8 tons, that load would amount to 50 tons.

It will again be remarked here, that if the inclination of the plane in question be

$$\frac{1}{e} = \frac{k}{2240} \cdot \frac{M''}{m},$$

and if the motion take place in ascending, the load which, on that plane, will correspond to the load M″ on a level, will be null. This circumstance readily explains itself, on observing that we have then

$$\frac{2240}{k} \cdot \frac{m}{e} = M'';$$

which indicates that, by reason of the inclination of the plane, the gravity of the engine alone is equivalent to the load M″ on a level, and consequently all that the engine can do will be to move itself up the plane. If the inclination be greater than that which we have just mentioned, a negative value will be found for the load of the engine, which would arise from the weight of the engine alone being already too great to represent the load M″ on a level.

Finally, in the case in which the motion is descending, and in which

$$\frac{1}{e} = \frac{k}{2240},$$

it will be found that the load of which the engine is capable is infinite; and in effect the inclination of the plane will be such, that the gravity of the waggons will compensate their friction, so that they will offer no resistance to the motion, and consequently the engine may draw an unlimited number of them.

3rdly. Besides the two problems which have just

occupied our attention, it may yet be required to determine what is the inclination on which a given load would be equivalent to another given load on a level. This research offers no difficulty; for the same relation obtained above, being resolved with reference to $\frac{1}{e}$ gives, when the motion is ascending,

$$\frac{1}{e} = \frac{k}{2240} \cdot \frac{M'' - M}{M + m};$$

and when the motion is descending,

$$\frac{1}{e} = \frac{k}{2240} \cdot \frac{M - M''}{M + m}.$$

In these two expressions, M still expresses the load on the inclined plane, and M″ the load on the level.

Thus, for instance, if we seek on what inclination a load of 50 tons, drawn up an inclined plane by an engine of 8 tons weight, is equivalent to a load of 86 tons on a level, we shall find the inclination of the plane to be $\frac{1}{600}$.

It must however be observed, respecting the three problems which have just been considered, that the loads on a level, corresponding to loads on given inclinations, are equivalent to them only as far as they represent the traction and the gravity of those loads; *thus far* then they may replace each other, but for this substitution to be exact, it must in no way affect the resistance of the air, which is always to be valued by the number of waggons of the real load, and not by the number of waggons which

would compose the fictitious load, if it were really to be drawn on a railway, practically and according to the ordinary manner of loading.

For example, when a load on a level represents a load drawn up an inclined plane, it is clear that its weight must be greater; and when it represents a load drawn down the plane, it will on the contrary have a less weight. In the former case, supposing the load on a level effectually prepared for conveyance, it would require a greater number of carriages than the real load, and in the latter case, it would require a less number. If then instead of computing the resistance of the air according to the number of carriages in the original load, it were valued according to the carriages which the transformed load supposes, the two loads thus considered would no longer offer an equal resistance. When therefore we say that two loads are equivalent to each other, it is not to be understood that they can, always and absolutely, replace each other, but merely that it is possible at the same velocity and with the proviso mentioned above.

Sect. II. *Of the velocity of locomotive engines on inclined planes.*

When a locomotive engine draws a train up an inclined plane, its velocity is necessarily diminished, and on the contrary its velocity is augmented when the engine draws its load down the plane. To be

enabled then to form a complete judgment of the influence of inclined planes on railways, it is necessary to examine within what limits these effects of diminution and increase of velocity are produced. For this reason we are now about to consider the motion of the engines, in ascending and in descending inclined planes.

When a locomotive engine ascends an inclined plane, its load immediately becomes greater, because the gravity of the train on the plane is added to the friction of the waggons. One would then be induced to think that the velocity must diminish in a degree nearly proportionate; but that is not the case, because, as the velocity of the engine diminishes, the resistance of the air diminishes very rapidly, since it varies in the ratio of the square of the velocity; and consequently there remains in the engine, so much the more force to apply to the traction of the load. For the same reason, the velocity, in descending inclined planes, does not increase indefinitely, as might be thought at a first glance.

This will easily be recognised on recurring to the practical formula which we have presented in Article III. of Chapter XII., for determining the velocity of the engine, with a given load and on a known inclination, namely:

$$v=\frac{784\ \mathrm{S}}{(1+\delta)\left[(6\pm g)\,\mathrm{M}\pm gm+uv^2\right]+\mathrm{F}+\dfrac{d^2\,l}{\mathrm{D}}(2736+p'v)}.$$

Suppose, in effect, an engine similar to that which we have already submitted to calculation in Chapter XII., or with the following proportions:

Diameter of cylinder, 11 inches, or $d = \cdot 917$ foot;
Stroke of piston, 16 inches, or $l = 1 \cdot 33$ foot;
Wheel, 5 feet, or $D = 5$ feet;
Friction, 103 lbs., or $F = 103$;
Weight, 8 tons, or $m = 8$;
Gross vaporization, at the velocity of 20 miles per hour, 65 cubic feet of water per hour, or *effective* vaporization $S = 48 \cdot 75$ cubic feet of water per hour;
Blast-pipe, 2·33 inches in diameter, which, for the vaporization supposed, gives $p' = \cdot 175$;
Additional friction, $\delta = \cdot 14$;
Effective pressure in the boiler, 70 lbs. per square inch.

Seeking the velocity which this engine will assume with a load of 56 tons gross, tender included, on different inclined planes, we obtain the results contained in the following Table.

Velocities of a locomotive of 65 cubic feet of vaporization, with a train of 56 tons gross, on divers inclined planes.

Direction of the motion.	Velocity of the engine, in miles per hour, the inclination of the plane being:				
	0	$\frac{1}{600}$	$\frac{1}{450}$	$\frac{1}{150}$	$\frac{1}{100}$
Ascending	25·10	22·02	21·01	14·90	,,
Descending	25·10	28·42	29·81	40·00	46·73

It appears from these results that, even in descending planes on which the waggons run of themselves, by virtue of their gravity, and aided by all the force of the engine in favour of the motion, the trains nevertheless assume but moderate velocities; and that in ascending rapid acclivities, the velocity likewise diminishes but in a very limited degree. With very heavy trains indeed, and with a more powerful engine, the velocity of descending trains might become much greater; but it would always remain more moderate than one might at first be induced to suppose it.

In performing the calculation of the velocity of trains descending inclined planes, it is to be observed that, when the inclination of the plane is greater than the angle of friction of the waggons, the resistance offered by the train itself becomes negative, because the gravity then predominates over the friction, that is, the term $(6-g)$ becomes negative. The only force the engine has then to surmount is therefore the resistance of the air, partly counterbalanced by the excess of the gravity over the friction; but that force suffices, as we see, promptly to limit the velocity of the motion. It is equally to be observed, on the same descents, that the greater the load, the more the velocity of the engine increases, which is the contrary of the effects produced, either in ascending a plane, or in traversing a level, or, finally, in descending a plane less inclined than the angle of friction.

Sect. III. *Of the velocity of descent of trains, on inclined planes where no use is made of the force of the engine.*

The researches which have just engaged us are relative to the ascent and descent of planes, on which the force of the engine is used to produce the motion of the train. This case invariably occurs in all questions of ascent, but it obviously does not always in questions of descent. In effect, the latter may be divided into three classes:

1st. Inclinations on which the gravity is less than the friction, and whereon the train could not advance without the help of the engine;
2nd. Inclinations on which the gravity exceeds the friction, and whereon the trains would descend of themselves, but with a velocity less than what the work requires;
3rd. Inclinations on which the gravity so much exceeds the friction, that the trains would acquire too great a velocity during their descent, if they were not restrained in their motion by the use of the brake.

The first case is evidently comprised among those which have been treated of in the preceding section; and it is the same with the two others, whenever it is thought proper to use the force of the engine, notwithstanding the inclination of the plane.

In the second case, there may occur a problem which we have not yet noticed: it is that of finding what vaporization the engine ought to have, or to apply, in order to communicate to the descending train a determined velocity. This problem would be solved by taking equation (7), Chapter XIII. Sect. II., which gives the effective vaporization of the engine for desired effects, and substituting in it for the friction, gravity, &c., the data proper to the inclined plane in question. It can therefore offer no difficulty, and we shall dwell no longer on it.

In the third case, it may be required to find what velocity the trains would attain of themselves during their spontaneous descent on the plane, and what effort the brake ought to apply, to reduce their velocity within certain fixed limits. This is the object of our inquiry at present.

When the inclination of a plane is such that, aided by the steam, the waggons would be liable to acquire a greater velocity than would be thought consistent with the safety of the passengers or the preservation of the engine and carriages, the engine-men suspend the action of the engine entirely. Then the motion is nothing more than the result of the natural gravity of the train on the declivity, and it is easy to obtain its valuation.

Suppose, in effect, the train to reach the summit of the plane with the velocity, already considerable, which results from the prior action of the engine;

it will first begin its motion on the plane with that same velocity, and will tend to augment it more and more, by reason of the constant action of the gravity. But it is clear that, in this case, the motive force will be nothing more than the excess of the gravity, above the friction of the waggons augmented by the friction of the engine; and the resistance will be precisely the resistance of the air. So long as the motive force predominates over the resistance, the motion will continue to accelerate; but as the motive force is constant, and as the resistance of the air on the contrary increases rapidly, there will be a point at which those two forces will become equal; and from that moment the motion will be uniform. Considering, in Chapter V., the motion of bodies committed to gravity on inclined planes, we have shown that this uniformity of motion will establish itself at the end of a limited time.

If then the train be supposed to have attained that uniform motion, the resistance of the air will be equal to the motive force. Now the motive force is known, since it is no other than the excess of the gravity above the frictions. Therefore the excess of the gravity above the frictions will give also the intensity of the resistance of the air during uniform motion; and consequently we may thence deduce the velocity of that motion, or the velocity which the train will necessarily acquire after a limited time of its descent. Hence, neglecting the

difference which existed, at the commencement of the motion on the plane, between the velocity of the train resulting from the previous action of the engine, and its definitive velocity resulting from gravity, we may take the uniform velocity which we have just determined, as that of the whole passage of that descent.

If, for example, we consider a train of 9 coaches and tender, weighing 50 tons, preceded by an engine weighing 8 tons, and suppose it placed on a plane inclined $\frac{1}{150}$, the gravity of the train and engine will be 866 lbs., the friction of the waggons will be 300 lbs., and that of the engine 100 lbs. nearly. Thus the motive force, and consequently also the resistance of the air during the motion, will be 466 lbs. Now the train offers to the resistance of the air an effective surface of 170 square feet. Hence the resistance of the air per square foot of surface, will be 2·74 lbs.; which gives for the velocity of the motion 31·94 miles per hour. If a similar calculation be made, for different cases, the following Table will be formed:

Velocity of descent of trains left to themselves on inclined planes.

Designation of the train.	Maximum velocity of the train, in miles per hour, the inclination of the plane being:		
	$\frac{1}{200}$	$\frac{1}{150}$	$\frac{1}{100}$
Train of 50 tons, tender included	23·40	31·94	44·36
Train of 100 tons, tender included	26·21	35·07	48·12

Such are then the velocities the trains would attain when abandoned to their own weight; but upon railways a maximum velocity is fixed for the descent of inclined planes, and that velocity is determined with a view to the preservation of the railway and carriages. If then we suppose that the greatest velocity of descent on inclined planes has been fixed at 26 miles per hour, as on the Liverpool and Manchester Railway, it is plain that in the different cases which we have just treated, the engine-men will be obliged to use the brake, to reduce the velocity to 26 miles per hour. Now as the resistance of the air against a train of 10 coaches and the engine, at the velocity of 26 miles per hour, is 309 lbs., the effective motive force must obviously, in all the cases, be reduced to that rate. In practice, this effect will be produced by guess and trial, by tightening the brake more or less; but it is easy to determine the friction which, in each case, the brake ought to exert in order to obtain the velocity desired. If, for instance, we consider the train of 50 tons descending a plane inclined $\frac{1}{150}$, the effort of the brake must obviously be $466-309=157$ lbs., and the calculation will be the same for any other case.

These examples show that, whether the force of the engine be employed wholly or partially, or the trains be left to themselves, or their speed be moderated by the application of the brake, it will be easy, in all cases, to determine their velocity on the inclined planes.

The same examples show that exaggerated fears have been entertained, in France, of the dangers which might result from the occurrence of declivities on railways, and that it was carrying the precaution too far to prohibit, in an almost absolute manner, inclinations greater than the angle of friction, on account of the danger to which they seemed to expose the descending trains. This apprehension was founded on the idea that, by the very fact of the trains rolling spontaneously down the planes, they might accelerate their velocity almost indefinitely. But the calculations which we have just presented prove that, even though the brakes should happen to give way, the velocity of descent of a train of 100 tons, which is one of the heaviest in use, would not exceed 48 miles per hour on an inclination of $\frac{1}{100}$. Now this velocity is itself comprised within the limits that powerful engines attain with light loads, and the Government has not as yet deemed it necessary to interfere in this respect. Besides, we have said that on rapid descents the brake is applied; and for above twelve years that the Liverpool and Manchester Railway has existed, the velocity of the heaviest trains has invariably been reduced to 22 and 26 miles per hour, on planes inclined $\frac{1}{96}$ and $\frac{1}{89}$, without any accident resulting from that cause. We hope then the conviction will prevail, that the only inconveniences attendant on declivities consist in the surplus of work they impose on the engines; and in that respect, it is

proper to leave to the companies who undertake railways, the care of judging whether it is more advantageous for them to make a tunnel or go round a hill, rather than crossing it by means of an inclined plane. But by refusing them the faculty of employing the latter means, it has often happened that expenses have been imposed on them, so heavy as to amount almost to a complete prohibition of the establishment of the railway.

Sect. IV. *Of the duration of the trip, and of the average velocity of the engines, on a system of successive inclinations.*

In the case of a train drawn on a railway which is either level, or of a uniform inclination, there can be no difficulty in finding the duration of the trip from one point of the railway to another. In effect, as the time employed by a body in traversing a given space with a uniform motion, is equal to the space traversed, divided by the velocity of the motion, it will suffice, first, to determine the velocity of the engine with the desired load, and then to divide the whole length of the way by the velocity of the engine, and the result will be the time sought or the duration of the trip.

For example, if an engine is to traverse a space of 30 miles, with a velocity of 10 miles per hour, the duration of the trip of 30 miles will be

$$\frac{30}{10} = 3 \text{ hours.}$$

But if the line to be traversed consist of a series of ascents and descents of various inclinations, the question will become more complex, without however presenting more difficulty.

In this case, the velocity of the engine, with the given load, on each of the inclinations to be traversed, must be sought, either by the formula (1 bis), Chapter XII., or by the means indicated in the preceding section; then the separate lengths of the inclinations must be divided, each by the respective velocity of the engine, which will give the time employed in traversing each inclination; and the sum of all the results thus obtained will be the total duration of the trip. Finally, dividing the whole distance by the total duration of the trip, the quotient will be the average velocity of the trip.

If, for example, it were found that the engine would perform 10 miles with the velocity of 10 miles per hour, 10 miles with the velocity of 20 miles per hour, and 10 miles at the velocity of 30 miles per hour, the total time of performing the 30 miles would be

$$\frac{10}{10}+\frac{10}{20}+\frac{10}{30}=1\cdot 83 \text{ hour};$$

and consequently the average velocity on the whole distance of 30 miles would be

$$\frac{30}{1\cdot 83}=16\cdot 4 \text{ miles per hour.}$$

In general, if the successive lengths of the inclined

planes to be traversed, be expressed by L_1, L_2, &c., and the respective velocities of the engine on those inclinations by V_1, V_2, &c., the time of performing the whole distance will be

$$\frac{L_1}{V_1} + \frac{L_2}{V_2} + \text{\&c.};$$

and the average velocity of the trip will be

$$\frac{L_1 + L_2 + \text{\&c.}}{\frac{L_1}{V_1} + \frac{L_2}{V_2} + \text{\&c.}}.$$

This question then can offer no difficulty.

Among the applications relative to this question, we may have to consider a series of ascents and descents between two points on a level, with a view to determine what disadvantage there will be, with regard to the duration of the trip, and for an engine and train of known weight, in following the undulating line, instead of the straight and level line which would join the two extreme points. This problem occurs whenever, in projecting a railway, it becomes necessary to choose between cutting through a hill and crossing it by means of inclined planes.

In this case, the calculation will be similar to the preceding. The velocity corresponding to the passage of the train over each inclination must be found first, and after having deduced from it the time employed in traversing all the inclinations, that time must be compared with the time the engine would require, according to equation (1 bis), to perform

the straight and level line which would join the extreme points.

If, for example, it be desired to know the time of traversing a total distance of 20 miles, and the average velocity of the same engine, which has been noticed in Sect. II. of this chapter, with its load of 56 tons gross, tender included, in following either a line entirely level, or a line of the same length, but consisting of two equal and contrary inclinations, referring to the velocities already obtained in Sect. II., we shall form the following Table:—

Time of traversing 20 *miles, and average velocity of a locomotive of* 65 *cubic feet of vaporization, with a load of* 56 *tons gross, on a system of equal ascents and descents.*

Object of calculation.	Designation of the line to be traversed.			
	10 miles on a level and 10 miles on a level.	10 miles ascending and 10 miles descending $\frac{1}{600}$	10 miles ascending and 10 miles descending $\frac{1}{400}$	10 miles ascending and 10 miles descending $\frac{1}{150}$
Time of traversing 20 miles, in minutes .	47·65	48·36	48·69	55·66
Average velocity of the trip, in miles per hour	25·10	24·81	24·64	21·56

We see by these results, that on a system of equal ascents and descents, compared with a level line of the same length, the engine will always be at a disadvantage with respect to the average velocity,

or the duration of the whole trip, since it here appears that the velocity, which was 25·10 miles per hour on a level, reduced itself successively to 24·81, 24·64, and 21·56, and the time of performing the whole distance increases in a corresponding manner, according to the system of planes over which the engine has to pass.

It will be remarked at the same time, that it would be quite inaccurate to take, as the average velocity of the passage of the two inclinations, the mean between the two velocities which we have obtained in Sect. II., for the ascent and descent of those inclinations, because those two velocities are not maintained by the engine during equal times.

Sect. V. *Of the average load of the engines, during their passage over a system of successive planes.*

When an engine ascends and descends several successive inclinations, its load varies considerably, since the gravity of the train now increases, now diminishes the original resistance of the train on a level. It is necessary then to be able to calculate the average load which results from these variations during the whole time of the trip.

For this purpose it will suffice first to calculate, by the means above indicated, the load on a level which corresponds to the traction of the train over each plane, and the time of traversing each respec-

tive plane, that is to say, the time during which the engine has to draw that load. Then, multiplying each load by the time during which it is applied to the engine, taking the sum of all these products, and dividing that sum by the total time employed in traversing all the planes, the result will be the average load of the engine during the trip.

Suppose, in effect, the question concern a system of two inclined planes: one on which the load is equivalent to 150 tons, and which requires 3 hours of time; the other on which the load is equivalent to 50 tons, and which requires 1 hour of time. It is clear that during the first hour the load of the engine is 150 tons; during the second and third, the load is still 150 tons; and during the fourth hour, the load is 50 tons. Hence, during each successive hour of the duration of the trip, the loads will be

$$\begin{array}{r} 150 \text{ tons} \\ 150 \\ 150 \\ 50 \\ \hline 500 \text{ tons}; \end{array}$$

and as the total trip has had a duration of 4 hours, we see that the average load of the engine during the whole trip, or per hour of work, will be

$$\frac{500}{4} = 125 \text{ tons}.$$

To obtain, therefore, the average load of the engine, each effective load must be multiplied by the time it is applied to the engine, the sum of all these products must be taken, and finally that sum divided by the total time of the trip.

Thus, in general, expressing by M_1, M_2, &c., the successive loads of the engine on different planes, by L_1, L_2, &c., the respective lengths of the planes, and by V_1, V_2, &c., the corresponding velocities,

$$\frac{L_1}{V_1}, \ \frac{L_2}{V_2}, \ \&c.$$

will be the times employed in traversing each of the successive planes; and

$$\frac{M_1 \frac{L_1}{V_1} + M_2 \frac{L_2}{V_2} + \&c.}{\frac{L_1}{V_1} + \frac{L_2}{V_2} + \&c.}$$

will be the average load of the engine during the whole trip.

If the line in question consist of ascents and descents traced between two points on a level, or of ascents and descents counterbalancing each other, the average load of the engine during its passage over those inclinations, will always be greater than it would be on the level line which would join the two extreme points. In effect, if we first calculate the effective loads, or the loads reduced to a level, which correspond to the passage of an engine of the

weight of 8 tons, drawing a train of 56 tons gross, tender included, over divers given inclinations, we shall obtain the following results :—

Effective loads of an engine of 8 *tons weight, drawing a train of* 56 *tons on divers given inclinations.*

Direction of the motion.	Effective load of the engine, in tons, the inclination of the plane being:			
	0	$\frac{1}{400}$	$\frac{1}{300}$	$\frac{1}{100}$
Ascending	56	95·83	109·17	215·33
Descending	56	16·17	2·83	—103·33

Then, recurring to the duration of the passage of the same engine with its load over the different planes, as obtained in the preceding section, and proceeding, as we have just indicated, to find the average load of the engine in ascending and descending different planes successively, we shall obtain the following Table :—

Average load of an engine of 8 *tons weight, traversing, with a train of* 56 *tons gross, a system of given ascents and descents.*

Object of calculation.	Designation of the line to be traversed.			
	10 miles on a level and 10 miles on a level.	10 miles ascending and 10 miles descending $\frac{1}{400}$.	10 miles ascending and 10 miles descending $\frac{1}{300}$.	10 miles ascending and 10 miles descending $\frac{1}{100}$.
Average load, in tons gross	56	61·04	65·21	127·37

It appears, from these results, that there is always a disadvantage in laying down a railway according to a line of ascents and descents, instead of tracing it according to the horizontal line which would join the extreme points ; also that this disadvantage will augment as the planes to be traversed are more inclined, and that it will always subsist even for planes less inclined than the angle of friction.

It will be remarked, that had we merely taken the mean between the ascending and the descending loads, on the different planes, we should have had 56 tons, in every case, for the average load of the engine. But that calculation would have been faulty, since, if we take as an example the two planes inclined $\frac{1}{450}$, the engine has to draw the load of 109·17 tons during 28·56 minutes, and the load of 2·83 tons during only 20·13 minutes; and simply taking the mean of the two loads, is by the fact supposing that the two planes are traversed in equal times.

Through not having made this distinction, some engineers have thought that, as long as the inclinations did not exceed that on which the waggons run of themselves, the traction of the engines remained the same as if the line were perfectly level. As their practice was to compute the average load by taking the mean between the ascending and the descending loads, they concluded that the surplus of traction in the one case was compensated by its diminution in the other; and thence the name of

normal inclinations was given to inclinations less than the angle of friction. But it is plain that no inclination on a railway can be called *normal*, since all slants, of whatever inclination they may be, are disadvantageous in all cases. We have, in effect, seen in the preceding section, that on a system of ascents and descents of any kind, the average velocity of the engines with the same load is diminished, or the time of traversing the same distance augmented; we here see that, on the same system of planes, the average load of the engine per hour of work is increased. On the other hand, it is obvious that the *useful* effect definitively produced remains always the same, since it consists solely in the conveyance of the load from one extremity of the line to the other. There can be no doubt, then, that the occurrence of ascents and descents on a railway is disadvantageous in all respects.

Sect. VI. *Of the quantity of work on a level, which corresponds to the conveyance of a given load, over a system of known inclinations.*

There is yet another research which necessarily presents itself with respect to railways consisting of a series of different inclinations; namely, that of the quantity of work on a level, and at a like velocity, which corresponds to the total work executed by the engine during its trip. We mean to say that, when an engine traverses a system of various inclinations,

it performs, in traversing each of those inclinations, a certain quantity of work, which is measured by the traction required of the engine and the length of the inclination, or the distance on which that traction is exerted. When the engine then has finished its trip, it has executed successively different quantities of work; and the object proposed is to find the quantity of total work thus done by the engine, and to deduce therefrom the work on a level, which would be equivalent to it.

This problem occurs whenever, after having observed the expenditure of fuel of an engine, in traversing a system of planes with a given load, it is required to deduce the expenditure of that fuel which corresponds to the traction of 1 ton 1 mile on a level. It is also the problem which occurs when, after having observed the expenses of maintaining and working the engines on a railway composed of ascents and descents, it is required to deduce what those expenses would be on a level line.

To obtain the solution of this question, we must first seek the quantities of work successively done in the conveyance of the train on each inclination, and their sum will give the work executed in the whole trip. Comparing afterwards this work with that which would be done in drawing a ton 1 mile on a level, we deduce its expression in tons drawn 1 mile on a level.

Now, the force necessary to overcome the friction

of the waggons placed on the plane, is known. Moreover, dividing the total weight of the train, augmented by that of the engine, and by that of the tender, if the latter have not been originally comprised in the weight of the load, by the number which represents the inclination of the plane, we have likewise the gravity. We can therefore calculate the traction required of the engine during its passage over each plane, and multiplying that traction by the distance on which it is exerted, we have the quantity of work performed during the passage of the inclination. Making successively a similar calculation for each plane, we may conclude the total work demanded of the engine during the whole trip; and, finally, knowing that the draught of a ton 1 mile on a level requires a traction of 6 lbs. 1 mile of distance, or a quantity of work of 6 lbs. raised 1 mile, we may definitively deduce the work, on a level, which corresponds to the total work of the engine.

To simplify this calculation, instead of seeking immediately the definitive work required of the engine on each inclination, by virtue of the friction and the gravity, we may, which amounts to the same, calculate first the work performed in overcoming the gravity of 1 ton on each successive inclination. Then, having once found this work, expressed in pounds raised 1 mile, knowing also that a weight of 6 lbs. is equivalent to the traction of 1 ton on a level, we may immediately express it in

tons drawn 1 mile on a level. After having obtained this expression for each of the successive planes, nothing remains but to take the sum of these expressions, in order to have the total work resulting from the draught of 1 ton over all the planes of the whole line. Consequently, multiplying this result by the number of tons which compose the total mass in motion, and adding to it the work done in overcoming the resistance of the air and the friction of the waggons, on the total length of the trip, we shall have definitively the work performed in the traction of the train over all the planes of the whole line. It is necessary only, before going any further, to add here two observations.

The first is, that it is proper to distinguish the ascents from the descents, and, to that end, care must always be taken to give to the work done in overcoming the gravity, the sign *plus* for those portions of the line which are to be ascended, because on those portions the gravity, and consequently the work which represents it, is to be added to the traction of the waggons; and the sign *minus* for those portions of the line which are traversed in descending, because on descents the gravity, on the contrary, comes in deduction of the work required of the engine, and is consequently to be subtracted. By this means, we have only to add, with their sign, all the quantities of work thus found, in order to deduce the definitive work done in overcoming

the gravity of 1 ton on the whole line of inclinations.

The second observation which we have to make is relative to planes more inclined than the angle of friction. It is known that on these planes the gravity exceeds the friction, so that the train might, in fact, continue its motion without the help of the engine. However, as for a railway enterprise it is not enough that the train move slowly onward, but it must assume and maintain the velocity fixed by the exigencies of the trade; as, moreover, the train cannot run of itself at any velocity on a descent, unless the gravity be capable of overcoming not only the friction of the waggons but that of the engine, it follows, finally, that it is only on planes sufficiently inclined for the gravity to be equal to the sum of the friction of the waggons, the friction of the engine, and the resistance of the air against the train at the desired velocity, that the effect of the engine can be dispensed with.

According to the velocities in use on railways at the present day, 25 miles per hour may be considered as the velocity generally adopted for a train of 10 carriages or 50 tons gross, exclusive of the tender, and about 20 miles per hour for that of a train of 20 waggons or 100 tons gross, exclusive of the tender. Admitting then these data, and taking, besides, 100 lbs. for the friction proper to an engine of 8 tons, it appears that the inclinations on which it would be possible to suspend the action of the

steam will be $\frac{1}{190}$ in the first case, and $\frac{1}{244}$ in the second. It may then be admitted, on an average, that, on a well-kept railway adapted to ordinary velocities, with well-constructed carriages, the trains will of themselves acquire a sufficient velocity, when the inclination is $\frac{1}{200}$; so that on such inclinations the action of the steam may be entirely suspended. This premised, it is visible that in seeking the quantities of work done by the engine in traversing a system of divers planes, we must set down zero for all descending planes inclined $\frac{1}{200}$ or more; that is to say, we must, for those planes, omit in the calculation both the gravity of the mass and the friction of the waggons, since these two quantities mutually destroy each other.

To give an example of this calculation, and to render the explanation of it perfectly clear, we will seek the quantity of work done by the locomotive engines of the Liverpool and Manchester Railway, in the conveyance of their load over the totality of the space which they have to traverse. As the calculation relative to the gravity is performed much more commodiously by way of a Table, we will here present it under that form. The first column of the Table contains the successive lengths of the line, the second indicates the respective inclinations of each of those distances, the third gives the gravity of 1 ton on the inclination considered; the fourth and last contains the product of that gravity by the distance traversed, that is, the work done in over-

coming the gravity; but, having been divided by 6, this work is transformed into tons drawn 1 mile on a level.

The signs placed before the numbers mark, as we have just said, the ascending or the descending planes. Thus the inclination $\frac{1}{1094}$ is a descent in going from Liverpool to Manchester, and therefore the work corresponding to the gravity has the sign *minus;* but it is an ascent when the line is traversed in the opposite direction, which causes it, in that case, to have the sign *plus*. The gravity on the inclinations $\frac{1}{2762}$ and $\frac{1}{4257}$ might have been neglected in this calculation, because in practice these inclinations may be treated as level lines.

Work done in overcoming the gravity on the Liverpool and Manchester Railway.

Section of the railway, from Liverpool towards Manchester.		Gravity of 1 ton on the inclination traversed.	Work done in overcoming the gravity of 1 ton	
Distances.	Inclinations.		From Liverpool towards Manchester.	From Manchester towards Liverpool.
miles.		lbs.	tons 1 mile on a level.	tons 1 mile on a level.
·53	0	0	0	0
5·23	d. $\frac{1}{1094}$	2·04	−1·78	+1·78
1·47	a. $\frac{1}{96}$	23·33	+5·71	,,
1·87	0	0	0	0
1·39	d. $\frac{1}{89}$	25·00	,,	+5·79
2·41	d. $\frac{1}{2762}$	·81	− ·32	+ ·32
6·60	d. $\frac{1}{849}$	2·64	−2·90	+2·90
5·62	a. $\frac{1}{1300}$	1·72	+1·61	−1·61
4·36	a. $\frac{1}{4257}$	·52	+ ·38	− ·38
29·48			+2·70	+8·88

This Table shows that the gravity of each ton of a train drawn from one end to the other of the Liverpool and Manchester Railway, requires from the engine, according to the direction of the motion, a quantity of work equivalent to 2·70 or 8·88 tons drawn 1 mile on a level. Expressing then by M_1 the weight of any train, by m the weight of the engine, and by C the weight of its tender supposed not included in the load M_1, the work done in overcoming the gravity of the train on the line, will be

From Liverp. to Manch. . . $2·70\ (M_1 + C + m)$ tons 1 mile;
From Manch. to Liverp. . . $8·88\ (M_1 + C + m)$ tons 1 mile.

But on the other hand, laying aside the descents more inclined than $\frac{1}{200}$, on which the engines are not made to work, the distance performed by the trains is 28·09 miles from Liverpool towards Manchester, and 28·01 miles in the contrary direction; and the friction of the carriages is to be overcome by the engine throughout the extent of this distance. Therefore, the quantity of work done in overcoming the friction of the carriages, for a load of $M_1 + C$ tons drawn from one end of the line to the other, will be

From Liverp. to Manch. . . . $28·09\ (M_1 + C)$ tons 1 mile;
From Manch. to Liverp. . . . $28·01\ (M_1 + C)$ tons 1 mile.

Hence, finally, adding the work done in overcoming the gravity to that which is done in overcoming the friction, the total work performed by the engine, in

the conveyance of the load M_1 along the whole line, will be

From Liverp. to Manch. . . $30{\cdot}79\ (M_1 + C) + 2{\cdot}70\ m$ tons 1 mile.
From Manch. to Liverp. . . $36{\cdot}89\ (M_1 + C) + 8{\cdot}88\ m$ tons 1 mile.

In these expressions, m represents the weight of the engine effecting the motion. It is understood then that if the train is drawn by two or more engines, m is to be replaced by the weight of those different engines united. Similarly, if a train is helped in a part of the trip by an assistant engine, the above quantity of work must receive an addition, corresponding to the gravity of the assistant engine and its tender, on the portion of the line which it has to traverse, and to the friction proper to that tender on the same distance. On the Liverpool and Manchester Railway, for ascending the two planes inclined $\frac{1}{89}$ and $\frac{1}{96}$, assistant engines are used, weighing with their tender about 18 tons. The addition to make on that account, for friction and gravity, is therefore, very nearly, 112 tons one mile in each direction; but as the assistant engines are used only for about half the number of the trains, allowance will be made for this circumstance by adding only a work of 56 tons one mile, for each train conveyed along the line. Consequently, observing finally that the average weight of the engines is 8 tons, and that of the tenders 6 tons, which gives $m = 8$, $C = 6$, we find that the work done by the engines, exclusive of the resistance of the air, in the convey-

ance of a train of M_1 tons along the whole line, is represented by the two following expressions:—

From Liverp. to Manch. . . . $30{\cdot}79\ M_1 + 262$ tons 1 mile;
From Manch. to Liverp. . . . $36{\cdot}89\ M_1 + 348$ tons 1 mile.

It is, however, to be remarked, that the result thus obtained only represents the work executed in the conveyance of the load, as taken independently of the resistance of the air against the train, and of divers other resistances which the engines have to overcome, such as their own friction, their additional friction, the pressure arising from the blast-pipe, &c. This result is to be considered, then, only as a rough estimate, whereon to ground approximate calculations, such as may in general be deemed sufficient in practice, but not as an exact and mathematical expression of the work executed in the motion of the train. The result of this research will nevertheless be rendered much more exact, by adding to the work done in overcoming the friction and gravity, that done in overcoming the resistance of the air against the train at the velocity fixed upon for the motion.

Thus, taking 22·5 miles per hour, as the average required velocity on a railway for general transit, and 15 carriages, exclusive of the tender, as the average load, we find that the resistance of the air against the train in motion will be 327 lbs., which is equivalent to the traction, on a level and at very little velocity, of a weight of 55 tons

gross. This traction is to be performed by the engine throughout all the length of the portions of the railway on which the action of the engine is not suspended. Consequently, in the case of the Liverpool and Manchester Railway, and at the above velocity, the resulting addition, in either direction, will be 1543 tons one mile; and thus the work done in conveying the load M_1, from one end of the line to the other, *including the resistance of the air* at the average velocity of 22·5 miles per hour, will be

From Liverp. to Manch. . . . . $30{\cdot}79\,M_1 + 1805$ tons gross 1 mile on a level, at very little velocity.

From Manch. to Liverp. . . . . $36{\cdot}89\,M_1 + 1891$ tons gross 1 mile on a level, at very little velocity.

The calculation which we have just performed would equally apply to every other line, with this difference, that if the velocity necessary for the conveyance were less than 20 to 25 miles per hour, as we took it above for railways of great velocity, the action of the engine might be suspended on descents of less inclination than $\frac{1}{200}$; and then, in the calculation of the work done by the engine, all the motion performed in descending inclinations thus fixed for the limit of the use of the engine, must be suppressed.

As a second example of the preceding calculation, we will seek the quantity of work executed

by the engines of the Stockton and Darlington Railway, in the conveyance of a train of waggons along that line. This research, besides, will be needful to us in the Appendix to this work, for deducing the expense of carriage on that railway.

We give, in the annexed Table, the section of the portion of that line traversed by the locomotives, and the quantity of work done in overcoming the gravity. As the speed on that railway is but 8 miles per hour, and the trains are composed of 24 waggons, which, with their load, weigh 95 tons gross; as the average weight of the engines is 10·5 tons, and that of their tenders 4·5 tons; and as, finally, the friction of the engines, which are but little taken care of on that line, may be estimated at 30 lbs. per ton instead of 15 lbs., we find that the inclination which is sufficient to make the trains descend, with the velocity fixed for the work, is $\frac{1}{270}$. Taking account then of this limit, to deduct from the total trip the planes traversed without the help of the engine, we form the following Table:

Work done in overcoming the gravity, on the Stockton and Darlington Railway (portion traversed by the locomotives).

Section of the railway from Brusselton to Stockton.		Work done in overcoming the gravity of 1 ton.	
Distances to be traversed.	Correspohding inclination.	From Brusselton to Stockton.	From Stockton to Brusselton.
miles.		tons 1 mile.	tons 1 mile.
·46	d. $\frac{1}{311}$	$-$ ·552	$+$ ·552
·06	d. $\frac{1}{325}$	$-$ ·069	$+$ ·069
·92	d. $\frac{1}{144}$	0	$+$ 2·385
1·45	d. $\frac{1}{121}$	0	$+$ 4·474
2·25	d. $\frac{1}{528}$	$-$1·591	$+$ 1·591
1·25	d. $\frac{1}{135}$	0	$+$ 3·457
1·01	d. $\frac{1}{352}$	$-$1·071	$+$ 1·071
1·76	d. $\frac{1}{135}$	0	$+$ 4·867
·20	d. $\frac{1}{896}$	$-$ ·189	$+$ ·189
1·75	d. $\frac{1}{1584}$	$-$ ·412	$+$ ·412
1·61	d. $\frac{1}{1408}$	$-$ ·427	$+$ ·427
1·64	d. $\frac{1}{204}$	0	$+$ 3·001
·23	d. $\frac{1}{713}$	$-$ ·120	$+$ ·120
2·09	d. $\frac{1}{2192}$	$-$ ·356	$+$ ·356
1·25	d. $\frac{1}{253}$	0	$+$ 1·845
·03	0	0	0
·81	d. $\frac{1}{226}$	0	$+$ 1·338
·05	d. $\frac{1}{487}$	$-$ ·038	$+$ ·038
·80	d. $\frac{1}{1584}$	$-$ ·189	$+$ ·189
1·16	d. $\frac{1}{104}$	0	$+$ 4·164
20·78		$-$5·014	$+$30·545

Consequently, calculating, as we did above, for the Liverpool and Manchester Railway, we find that on that portion of the railway from Stockton to Darlington on which the locomotives run, the conveyance of any load M_1, expressed in tons gross, exclusive of tender, requires of the engines, inde-

pendently of the resistance of the air, a quantity of work represented, in tons drawn 1 mile on a level, by the following expressions:

From Brusselton to Stockton . . . $5\cdot\ 5\ M_1 -\ 28$ tons gross 1 mile on a level;
From Stockton to Brusselton . . $51\cdot 33\ M_1 + 552$ tons gross 1 mile on a level.

If it be desired, moreover, to introduce in the calculation the resistance of the air against the trains, the work done by the engines in drawing a train of 24 waggons at the velocity of 8 miles per hour, will be

From Brusselton to Stockton . . . $5\cdot\ 5\ M_1 +\ 70$ tons gross 1 mile on a level, at very little velocity.
From Stockton to Brusselton . . $51\cdot 33\ M_1 + 745$ tons gross 1 mile on a level, at very little velocity.

It is to be remarked, that when, in calculations of this kind, there occurs an incline followed by an equal contrary incline, and when their inclination is not sufficient for the action of the steam to be dispensed with during the descent, the computation of the definitive work done by the engine in traversing the two inclines will give the same number as if the line had been level. It is thence to be concluded, that taking, as we have done, the resistance of the air at its average value on all the portions of the trip, the work done in the conveyance of the train on the two inclines will be the

same as on a level. But this result arises simply from this, that in supposing the resistance of the air constant, we make a supposition favourable to the case of ascents and descents. In effect, if we refer to Sect. II. of the present chapter, and seek the resistance of the air against a train of 56 tons gross drawn by a locomotive of 65 cubic feet of vaporization, traversing either a level line or a system of given ascents and descents, we shall invariably find that the resistance of the air is less on the level line, though the average velocity is greater; and this is occasioned by the resistance of the air increasing as the *square* of the velocity. Thus, for instance, on two slants inclined $\frac{1}{150}$, the velocities of the train will be successively 14·90 and 40·00 miles per hour, which, for 10 carriages besides engine and tender, will produce a resistance of the air, first of 114 lbs. and afterwards of 817, or at a medium 465 lbs.; and on the level portion, at the velocity of 25·10 miles per hour, the resistance of the air will be only 319 lbs.

We are then finally to conclude, from the divers researches relative to ascents and descents, compared with the same length of road traversed on a level:

That on a system of ascents and descents, the work performed by the gravity of the train in descending an incline, may compensate the work required from the engine by that same gravity in ascending the contrary incline; but that in taking account of all

the circumstances of the motion, the average velocity of the engine will be reduced, its average load augmented, and the duration of the trip increased; whence will result a loss of time, more wear and tear of the engine, and an increased consumption of fuel.

Sect. VII. *Of the means of ascending inclined planes on railways.*

From what has just been seen, inclined planes are always a great obstacle on railways; they diminish the velocity of the conveyance, and augment the average traction of the engine. Besides this, to be enabled to ascend them, it is necessary to reduce the load of the engines below what they could draw on a level; and we have seen that, with regard to fuel, the engines work to greater advantage inasmuch as their load is greater. Finally, the use of the brake in descending inclined planes causes rapid destruction of the rails. It is therefore very important, in establishing a railway, to avoid inclined planes as much as possible.

When, however, inclined planes are unavoidable, there are four means of effecting the passage over them: 1st, by employing a stationary steam engine, which performs the traction of the train by means of ropes; 2nd, by employing an assistant locomotive engine, which pushes the train from behind and drives it to the summit of the plane; 3rd, by raising

the pressure of the steam in the boiler of the engine so, as to make it capable of a greater effort, with a proportionate diminution of velocity; and 4th, by reducing the load of the engines so as to enable them to ascend the planes without additional help.

Stationary engines always obstruct in some way the prompt execution of the work, and they expose the trains to accident, if the rope used for the traction should happen to break. Assistant engines, which want a fire kept up, even in the intervals of their work, are an increase of expense to the companies, and consequently oblige them to raise their prices. The augmented pressure in the boiler is dangerous to the safety of the engines and the passengers. Finally, the diminution of the load is a loss to the companies, since more trips are required to perform the same work.

When, therefore, a railway contains inclined planes, we have only the choice of the inconveniences, and it is only by an attentive examination of the circumstances of each particular case, that the best mode of traversing them can be decided upon. Some general ideas, however, on this subject, may be formed beforehand, by considering the surplus of traction required by a given inclination.

1st. On a plane inclined $\frac{1}{100}$ the gravity of 1 ton is 22 lbs., that is to say, about four times the friction proper to the waggons. The resistance opposed to the motion becomes then immediately five times as much as it was on a level. Besides, the engine

must overcome its own gravity, which, for an engine of 12 tons, amounts to 269 lbs.; but as, on the other hand, the diminution of the velocity of the train, in ascending the incline, immediately produces a reduction in the resistance of the air and in that arising from the blast-pipe, we will neglect at the same time these opposite circumstances. Thus, the train, as soon as it reaches the foot of the ascent, offers about five times its resistance on a level; and consequently, if the engine be supposed to have previously drawn its full load on a level, there will need five engines to get that load to the top of the plane. Now, it is readily conceived that, to prevent the expenses from becoming too great, the passage of ascents ought in no case to require more than one assistant engine. It is evident, besides, that this can take place on an inclination of $\frac{1}{100}$, only when the load given to the engines is limited to about half what they could really draw on a level; for, being once arrived at the foot of the plane, that load becoming five times as great, will be $2\frac{1}{2}$ times the maximum load of which the engine is capable, and consequently an assisting engine somewhat stronger than the trip engine will suffice to drive the train to the summit of the plane. Thus, we see firstly that a plane inclined $\frac{1}{100}$ may be traversed by means of one assistant engine, provided the load imposed on the engines be not greater than about half their maximum load.

2nd. Should the ascent be inclined more than

$\frac{1}{100}$, it might still indeed be traversed with a single assistant engine; but then it is obvious that the load of the engines on a level must be reduced below what we have just supposed; and there would no doubt be few cases, at least on railways destined to the simultaneous conveyance of goods and passengers, on which it would be found advantageous to fix the load of the engines below the half of their maximum load. We may therefore say generally that an inclination of $\frac{1}{100}$ will be nearly the limit of ascents on which assistant engines may be employed, and that, for greater inclinations, recourse must be had to stationary engines.

3rd. On a plane inclined $\frac{1}{300}$, the gravity of a ton is 7·50 ℔s., and consequently the total resistance of the train becomes about double what it would be on a level. An engine may then without assistance ascend an acclivity of that inclination, provided its load on a level do not exceed the half of what it might be. We may therefore consider a plane of this inclination as being nearly the most inclined that can be admitted on a railway without being constrained to employ assistant engines.

Thus, we are led to the following general conclusions:—

1st. On planes whose inclination does not exceed $\frac{1}{300}$, the traction may be performed without additional help;

2nd. On inclinations comprised between $\frac{1}{300}$ and

$\frac{1}{100}$, it will generally be necessary to have recourse to assistant engines;

3rd. On planes more inclined than $\frac{1}{100}$, it will most commonly be found advantageous to employ stationary engines.

Nevertheless we here repeat that the attentive examination of the circumstances of each case, can alone fix the choice in a decisive manner, and it is only with a view to indicate how that examination should be proceeded in, that we have entered into the foregoing considerations.

SECT. VIII. *Of the best line for a railway between two given points.*

Finally, before terminating this chapter, we have still a question to treat of, namely: the choice to be made between divers lines, with ascents and descents, proposed for a railway to be established between two determined points.

What has been said of the velocity, the duration of the trip, and the effective load of the engines, on a system of ascents and descents, includes all the elements of calculation that the present question requires; for, supposing the different plans executed, and the projected lines traversed by the same locomotive engine, with the same load, we may immediately find the average velocity which would take place on each, the time of traversing its total length, and, lastly, the quantity of work done by the engine

in the conveyance of a given load from one extremity of the line to the other. This question, therefore, offers no remarkable difficulty; but to facilitate its solution, we think it useful to explain more precisely the proceeding to be followed.

In order to solve the question proposed, the following way may be used:

1st. Since the nature and quantity of the goods to be carried are known, the number of trips per day will be fixed first of all, and consequently the average load which the engines will have to draw. This done, in recurring to the considerations presented in Chapter XIII., the width of way to be adopted will be decided upon, as well as the dimensions and weight of the locomotive engines to which it may appear advisable to give the preference.

2nd. A Table of the velocity, the time of traversing 1 mile, and the load on a level, of the engine, when passing, with its train, over divers planes more or less inclined, will be calculated.

Afterwards, having the section of the different lines proposed, one of them will be adhered to; then taking successively each of its inclinations, and seeking in the Table the inclination which approaches nearest to the one considered, there will be found annexed to it the velocity, the time of traversing 1 mile, and the corresponding load of the engine. Consequently, multiplying the time of traversing 1 mile by the length of the plane, we

shall have the time employed in traversing that plane; and multiplying the load on a level, by the same distance, we shall have the quantity of work done by the engine in traversing the plane in question.

Performing therefore the same operation for all the different planes which compose the line, taking the sum of all the partial times employed to cross these planes, and of all the quantities of work executed by the engine, we shall have the total duration of the trip over the line considered, and the total work done in the conveyance of the load from one end of that line to the other.

Thus, operating in the same manner for the different lines proposed, we shall have the total duration of the trip over each of them, and the quantity of work, in tons drawn 1 mile on a level, done by the engines in the conveyance of the determined load between the two given points. Afterwards, multiplying this last number by the amount of the expense of draught per ton per mile on a level, as will be indicated in the Appendix, we shall have the expense necessary for the traction on the line; adding thereto the other accessory expenses, which will likewise hereafter be given, we shall conclude the total expense of working the line; and lastly, computing the interest of the capital necessary for the execution of each line, and adding it, we shall have the total amount of expense corresponding to each line proposed.

Thus, with regard both to the duration of the trip between the two given points and the expenses of the work, every means will be afforded of comparing together the different lines projected.

To show the manner of forming the practical Table just mentioned, we will suppose to have been adopted a way 5 feet wide, an average load of 50 tons gross, exclusive of tender, and a locomotive of 65 cubic feet of vaporization with the dimensions indicated in Article III. Chapter XII., excepting the pressure in the boiler, which we will suppose 70 lbs. per square inch. With these the following Tables will be formed, and employed as has been indicated above.

Practical Table of the velocity, time of traversing 1 *mile, and load on a level, of a locomotive of* 65 *cubic feet of vaporization, &c., on divers given planes.*

Designation of the slant.	Velocity of the engine, in miles per hour,		Time of traversing 1 mile,		Load of the engine referred to the level,		Observations.
	without assistance.	with assistance.	without assistance.	with assistance.	without assistance.	with assistance.	
ascents.	miles.	miles.	minutes.	minutes.	tons gross.	tons gross.	
0	25·10	,,	2·382	,,	56·0	,,	
$\frac{1}{1000}$	23·53	,,	2·550	,,	79·8	,,	
$\frac{1}{600}$	22·02	,,	2·725	,,	95·8	,,	
$\frac{1}{500}$	21·46	,,	2·796	,,	103·8	,,	
$\frac{1}{400}$	20·32	,,	2·953	,,	115·7	,,	
$\frac{1}{300}$	19·09	,,	3·143	,,	135·7	,,	
$\frac{1}{250}$	18·10	,,	3·315	,,	151·5	,,	
$\frac{1}{200}$	16·91	22·97	3·548	2·612	175·5	103·8	One assisting engine, same force as the first.
$\frac{1}{175}$	15·94	22·02	3·764	2·725	192·5	114·2	do.
$\frac{1}{150}$	14·90	20·92	4·027	2·868	215·3	128·0	do.
$\frac{1}{125}$	,,	19·18	,,	3·128	,,	147·5	do.
$\frac{1}{100}$	,,	17·18	,,	3·493	,,	176·7	do.

Practical Table of the velocity, time of traversing 1 mile, and load on a level, of a locomotive of 65 cubic feet of vaporization, &c., on divers given planes.

Designation of the slant.	Velocity of the engine, in miles per hour,		Time of traversing 1 mile,		Load of the engine referred to the level,		Observations.
	regulator open.	regulator shut.	regulator open.	regulator shut.	regulator open.	regulator shut.	
descents.	miles.	miles.	minutes.	minutes.	tons gross.	tons gross.	
0	25·10	,,	2·382	,,	56·0	,,	
$\frac{1}{1000}$	27·12	,,	2·212	,,	32·2	,,	
$\frac{1}{600}$	28·42	,,	2·111	,,	16·2	,,	
$\frac{1}{500}$	29·21	,,	2·054	,,	8·2	,,	
$\frac{1}{400}$	30·43	,,	1·972	,,	— 3·7	,,	
$\frac{1}{300}$	32·15	,,	1·866	,,	— 23·7	,,	
$\frac{1}{250}$	33·63	,,	1·784	,,	— 39·5	,,	
$\frac{1}{200}$	35·89	23·34	1·672	2·571	— 63·5	0	Regulator shut.
$\frac{1}{175}$	37·46	27·28	1·602	2·199	— 80·5	0	do.
$\frac{1}{150}$	40·00	30·00	1·539	2·000	—103·3	0	Brake used.
$\frac{1}{125}$	42·58	30·00	1·409	2·000	—135·1	0	do.
$\frac{1}{100}$	46·73	30·00	1·284	2·000	—183·0	0	do.

In making the requisite comparisons between different lines proposed, the above Tables may be used, without calculating them again especially for each case. It must only be observed, that the Tables are strictly exact for the case of a way 5 feet wide, a load of 50 tons, and an engine similar to the engine supposed. Consequently, in the question of a railway on which other loads or other engines are intended, the comparison by means of these Tables must no longer be considered in any other light than as an approximation, that may require to be confirmed by an ulterior calculation. In the case then wherein such confirmation should seem necessary, the calculation must be repeated with more precision, taking for each proposed line its true inclination, and applying even to each line the width of way, the load, and the locomotive likely to give the most advantageous results. For those calculations we refer to what has been said in the different sections of this chapter.

In the preceding Tables, we have supposed the engine to have help, as soon as its velocity, on the ascents, should lower to about 15 miles per hour; the action of the steam to be suspended, on the descents, as soon as the velocity should tend to exceed about 30 miles; and, lastly, the brake to be used, to limit the speed to that rate, on all descents whereon the trains would of themselves assume too rapid a motion. These are, in fact, the limits generally adopted on railways at this time.

CHAPTER XVIII.

OF CURVES.

Sect. I. *Of the effects of curves on railways.*

Curves in railways present inconveniences which are by so much the greater as their degree of curvature is greater.

These inconveniences are of three kinds: 1st. When a waggon moves in a curve, the wheel which follows the outer rail necessarily goes over more ground than that which follows the inner rail. Now, in waggons at present in use, the two wheels of the same pair are not independent of each other, but are fixed invariably on the axle which turns with them. Therefore the distance described by the one cannot be less than the distance described by the other, except the latter be drawn without turning over the difference between the two distances to be described. This is in consequence an additional resistance offered to the motion.

2nd. The centrifugal force created in the passage of the curve, by virtue of the velocity of the motion, may urge the waggons outwards, so far as to produce a contact and consequently a friction of more or less energy of the flange of the wheel against the

outer rail; and the resistance produced by this cause is much more injurious than the former one, because the friction takes place on the whole of the distance performed by the wheel, and not merely on the difference of the distances performed by the two wheels.

3rd. Finally, the centrifugal force of the motion may be such as not only to press the flange of the outer wheel against the outer rail, but by pushing the wheel violently in a direction tangential to the curve, it may drive the flange of the wheel over the rail, and thus throw the train out of the rails.

We are about to consider successively these different effects of curves.

Sect. II. *Of curves the resistance of which is corrected by the conical inclination of the wheels of the waggons.*

The waggon wheels in use on railways are not of a cylindrical form. On railways of about 5 feet width of way, they are made of 3 feet in diameter at their inner edge, near the flange, and 2 feet 11 inches at their outer edge. The wheel is originally cylindrical, but the conical inclination is produced by the addition of a tire or band of wrought iron, which gives to the wheel its definitive diameter, and whose thickness on one side is half an inch less than on the other. Figure 29 represents the shape of this tire on a scale of $\frac{1}{4}$ of its real size. The

width of the tire being $3\frac{1}{2}$ inches, its conical inclination is $\frac{1}{2}$ inch on $3\frac{1}{2}$ inches, or $\frac{1}{7}$.

The original object of this form of wheel is to prevent a strong side wind, or the accidental depression of one of the rails, from driving the waggons on one side of the road, and thereby producing a friction of the flange of all the wheels of that side against the lateral surface of the rail, that is to say, a considerable resistance against the motion. By means of the above-mentioned disposition, this lateral displacing of the train becomes more difficult; and if nevertheless, from any cause, it do take place, and the waggons have been momentarily thrown on one side of the railway, the wheels on that side immediately increasing in diameter, begin to advance quicker than those on the opposite side, and consequently bring back the train to its normal position between the rails.

The conical inclination of the wheels suffices, of itself, to remedy the inconveniences of the passage over curves, when the degree of curvature of the latter does not exceed certain limits. In effect, if the two rails of the road be supposed exactly level one with the other, it is plain that in the passage along the curve, the centrifugal force of the motion will drive the waggon towards the outer rail. But gradually as the waggon is thus laterally displaced, the wheel on the outer side turns, by reason of its conical form, on a circle of still greater and greater diameter, and the inner wheel, on the contrary, turns on a diameter still less and less. In this state

of things, the two wheels of the same pair assume, by the fact, different diameters. Moreover, it is the outer wheel which acquires the greater diameter, or which performs the greatest distance in the same time; consequently the waggon now tends, of itself, to turn in the direction of the curve. It will readily then be conceived how this disposition of the wheels may remedy the inconveniences of certain curves, but it will now be proper to particularize still further the effects which are then produced.

The calculation of these effects evidently depends on two things: the intensity of the centrifugal force produced by the motion of the waggons in the curve, and the intensity of the centripetal force produced at the same time by the inequality of the wheels of the waggons. We shall then, first of all, call to mind the value of those two forces.

The centrifugal force, in the curve whose radius of curvature is ρ, has for its expression, representing the velocity of the motion by V, and the mass of the moving body by m,

$$f = m \frac{V^2}{\rho};$$

but P being the weight of the same body, and g the accelerating force of gravity, we have

$$P = gm, \text{ whence } m = \frac{P}{g}.$$

Therefore the centrifugal force has also the value

$$f = \frac{P}{g} \cdot \frac{V^2}{\rho};$$

which is the expression of the centrifugal force for a body of a given weight P, set in motion with the velocity V, in a curve whose radius of curvature is ρ.

In this expression, g is the accelerating force of gravity, or, as is well known, double the space described in the unit of time by a falling body in a vacuum. Taking the second as the unit of time, and the English foot as the unit of space, we have $g = 33$. Referring then to the same units the velocity V and the radius of curvature ρ, we shall have the measure of the centrifugal force expressed by its ratio to the weight P, or represented by a weight. For instance, if the velocity of the motion be 20 miles per hour, or 29·3 feet per second, and the radius of curvature be 500 feet, the centrifugal force will be

$$f = \mathrm{P} \times \frac{\overline{29{\cdot}3}^2}{33 \times 500} = \frac{1}{19}\mathrm{P},$$

that is to say, in this case the centrifugal force will be $\frac{1}{19}$ of the weight of the moving body.

It clearly appears that, when the velocity of the motion and the radius of the curve are known, the centrifugal force which urges the body out of the curve is easily found. We now pass on to the centripetal force produced by the inequality occasioned in the wheels of the waggon, by virtue of its lateral deviation.

When two wheels joined invariably together by

the same axle, roll on unequal circumferences, or, in other words, cease to be equal to each other, it is clear that instead of together forming a cylinder, they form a rolling cone. If *ab* and *cd* (fig 30) represent the respective diameters of the two wheels, and the extremities of those diameters be joined by straight lines, these will meet at a certain point *o*, which will be the vertex of the rolling cone formed by the two wheels; and the motion of the waggon borne on the two wheels will be the same as that of the cone *cod*.

But when a cone or frustum of cone is laid flat, or along one of its generative lines, on a horizontal plane, and it is urged onward by a force applied at its centre of gravity, suppose at *m*, it tends to assume a circular motion round its vertex *o*; and if we wish to prevent it following that curve, and to make it move straight forward, the force to be overcome will be a force precisely equal, and contrary to that which it would be necessary to apply to a body directed in a straight line, to curve its direction according to the circumference of the circle described by the point *m* round the point *o*. Now that force is the centrifugal force in the circle whose radius is *om*. Denoting then by ρ' the radius of that circle, which depends on the difference of diameter of the two wheels, and preserving the other notations as above, the centripetal force thus created by the motion of the cone, will have for its value

$$\frac{P}{g} \cdot \frac{V^2}{\rho'} .$$

Moreover, putting D' and D'' for the respective diameters of the two wheels, and e for the width of the road, or the space which separates the wheels, it is plain, from the figure, that we have the proportion

$$D'' : D' : : \rho' + \frac{e}{2} : \rho' - \frac{e}{2};$$

whence we derive

$$\rho' = \frac{e}{2} \cdot \frac{D'' + D'}{D'' - D'}.$$

But on the other hand, if the tire of the wheel is inclined $\frac{1}{7}$, as has been shown above, every inch of lateral deviation of the waggon, will produce in the wheel a difference of radius of $\frac{1}{7}$ inch, or a difference of diameter of $\frac{2}{7}$ inch. More generally, if $\frac{1}{a}$ express the inclination of the tire of the wheel, a deviation of the waggon expressed by λ will produce in the wheel a difference of diameter expressed by

$$\frac{2\lambda}{a}.$$

So that if D represent the original diameter of the wheel, and D' its diminished diameter, corresponding to the deviation λ, we have

$$D - D' = \frac{2\lambda}{a};$$

and similarly, the opposite wheel will receive an increase of diameter expressed by

$$D'' - D = \frac{2\lambda}{a}.$$

But by adding and subtracting these two equations we have

$$D'' - D' = \frac{4\lambda}{a}$$

and

$$D'' + D' = 2D.$$

Hence, finally, the centripetal force above, produced by a given lateral deviation λ, is expressed by

$$\frac{P}{g}V^2 \cdot \frac{4\lambda}{aeD}.$$

Thus, we have the centrifugal force produced in the waggon by the fact of its motion in the curve, and the centripetal force produced in the same waggon by the conical inclination of its wheels. But it is to be observed, that the former of these forces is constant for a given train, curve, and velocity; whereas the second varies with the lateral deviation λ of the waggon. As soon then as the waggon enters the curve, the centrifugal force will begin to exert its effect; it will drive the train towards the outer rail; a certain deviation λ will be produced, and, as its consequence, a centripetal force which will increase more and more. But since the centrifugal force is constant, whereas the centripetal force on the contrary is increasing, and as these two forces act in contrary directions on the waggon, they will quickly settle at a point where they will hold

each other in equilibrium. Then the waggon will cease to obey the centrifugal force, and will no longer be driven out of the curve.

The point at which the two forces will be equal is given by the equation

$$\frac{P}{g} \cdot \frac{V^2}{\rho} = \frac{P}{g} \cdot \frac{V^2}{\rho'},$$

or

$$\frac{P}{g} \cdot \frac{V^2}{\rho} = \frac{P}{g} \cdot V^2 \frac{4\lambda}{aeD};$$

which gives

$$\rho' = \rho, \text{ or } \lambda = \frac{aeD}{4\rho}.$$

As soon as the lateral deviation of the train shall have attained this point, it is clear that the waggons will continue their motion without having any tendency to leave the rails, that is to say, not only without risk of being thrown off the road, but even without the flange of the wheels being brought into contact with the outer rail. Besides, since we have at the same time $\rho' = \rho$, that is to say, since the vertex of the fictitious cone, formed by the system of the two wheels, will coincide with the centre of the curve, it is evident that the waggon will turn exactly with that curve without any dragging of one of the wheels on the rail.

Thus, on all curves on which the waggon may be sufficiently displaced, the effect of the curve will be corrected. But in the construction of railways, it is usual to give but half an inch of play to the waggons, on each side, on the railway; that is to say,

that during the normal position of the waggon between the rails, the beginning of the flange of each wheel is ½ inch from each rail. The greatest value therefore that can be given to λ, without making the flange of the wheel rub, is ½ inch, or ·0417 foot; and consequently the utmost curve that can be remedied by the conical inclination of the wheels, will be given by the value of ρ which corresponds to that maximum deviation, in equation

$$\lambda = \frac{aeD}{4\rho}.$$

Making then this substitution, and replacing at the same time a, e and D by their ordinary values, namely, $\frac{1}{a} = \frac{1}{7}$, $e = 4{\cdot}70$ feet, and $D = 3$ feet, we have for the least possible radius of curvature,

$$\rho'' = 592 \text{ feet.}$$

Consequently, it appears that with the conical inclination adopted, of $\frac{1}{7}$ for the tire of the wheel, and the play of the waggons ½ inch on the rails on each side, there may be constructed on railways curves of 600 feet of radius, without the flange of the outer wheels of the waggon being exposed to touch the rails on that side. As, however, this result supposes the two rails exactly level with each other, and that there might occur, during the work, an accidental depression of the outer rail, which would expose the flange of the wheel on that side to rub against the rail, we will, for greater security, limit the foregoing result to curves having 1000 feet of radius.

It must however be added, that there exists, in the passage of curves, a particular cause of resistance which we have not yet treated of, and which subsists notwithstanding the conical inclination of the wheels. It consists in this, that the two axles of each waggon are parallel to each other, whereas for the wheels to turn freely along the curve, like the cone to which we have assimilated them, the two axles ought to be convergent, on the side of the centre of the curve, and ought to concur precisely to that point. But as long as the question regards only curves of 1000 feet of radius, this circumstance may very well be neglected. In effect, the width of the way being 5 feet or $\frac{1}{200}$ of the radius of the curve, it is plain that for the axles to converge to the centre of the curve, their distance apart, on the side of the inner rail, should be $\frac{1}{200}$ less than on the side of the outer rail. Now the distance between the axles in their parallel position is about 5 feet or 60 inches : the inclination suitable to them would then be $\frac{1}{200}$ of 60 inches or 3-tenths of an inch ; and this small quantity is to be divided into quarters between the four extremities of the axles, which would make 7-hundredths of an inch at each of these points. But as so very small a measure is quite inconsiderable in practice, and as, besides, the flexibility of the springs on which the axles are mounted easily yields to so slight a deviation, we deem it perfectly needless to dwell on this circumstance. Curves therefore of a radius not less

than 1000 feet, may without inconvenience be constructed on railways.

By augmenting the play of the waggons on the railway, or the conical inclination of the wheels, this faculty might be extended to curves of less radius; but as it might be apprehended that the result would be a continual rocking of the waggons during their motion on the straight parts of the railway, we limit our views here to the determining of the curvature which is possible in the present state of things.

Sect. III. *Of the superelevation of the outer rail to be employed in curves whose curvature is not corrected by the conical inclination of the wheels.*

From what has just been seen, if a curve had a radius of curvature less than 1000 feet, and if nothing else were changed in the ordinary disposition of the rails, the flange of the outer wheel might come in contact with the rail on that side, before the proper deviation of the waggon could oppose a sufficient counterweight to the centrifugal force which produces that motion. The result would be not only a friction of the flange against the rail, but a possibility of the train itself being thrown off the rails. It will therefore be proper to consider what are the means of preventing that effect.

Now it is evident that by giving, throughout the curve, a superelevation to the outer rail above the inner, we shall make the railway form a plane

inclined in the direction of its width. The waggons placed on this inclined plane must, by virtue of their gravity, slide towards the inner rail, which is the lowest. On the other hand, the centrifugal force drives them towards the outer rail, which is higher. We thereby then create a counterpoise to the centrifugal force. Thus, by this disposition, we are enabled to prevent the waggons being thrown off the line.

But it is to be remarked, that since the waggons may always deviate half an inch laterally, without the flange of the wheel touching the rail, this deviation must first be taken advantage of to balance a portion of the centrifugal force. It is simply then the remainder, or the difference between the centrifugal force and the centripetal force arising from the greatest deviation of the waggons, that we need counteract by means of the superelevation of the outer rail.

If we denote by y the superelevation of the outer rail above the inner, since e expresses the width of the way, the inclined plane on which the waggons are placed, during the passage of the curve, will be inclined $\frac{y}{e}$; and consequently the gravity of the waggons will draw them towards the inner rail with the force

$$P \times \frac{y}{e}.$$

Now it is required that this force, joined to the centripetal force due to the greatest possible deviation of the waggons on the rails, hold the centri-

fugal force in equilibrium. Calling then ρ' the radius of curvature corresponding to the greatest lateral deviation of the waggons, as was found in the preceding section, we shall have

$$P \cdot \frac{y}{e} + \frac{P}{g} \cdot \frac{V^2}{\rho'} = \frac{P}{g} \cdot \frac{V^2}{\rho},$$

which gives

$$y = e\frac{V^2}{g}\left(\frac{1}{\rho} - \frac{1}{\rho'}\right).$$

Consequently, substituting for ρ' its value already found, $\rho' = 1000$ feet, and at the same time replacing e and g by their corresponding values, namely, $e = 4{\cdot}70$ feet and $g = 33$ feet, it is plain that, for every curve, it will be easy to determine the superelevation to be given to the outer rail, to counterbalance the centrifugal force, and to displace the waggon as much as may be possible, without however making the flange of the outer wheel rub against the rail.

It must however be added here, that as the necessary superelevation, or the value of y, increases in the ratio of the square of the velocity of the motion, it is indispensable to calculate y, not for the average velocity of the motion, but for the greatest velocity the trains can acquire. Otherwise the superelevation of the rail would no longer suffice for cases of very great velocity, and accidents might happen in the curves.

Performing the calculation for different velocities, and for a railway 5 feet wide, we obtain the following results :

Table of the superelevation to be given to the outer rail in curves.

Designation of the waggons and the way.	Radius of the curve.	Superelevation to be given to the outer rail, in inches, the maximum velocity of the motion, in miles per hour, being:				
		20 miles.	30 miles.	40 miles.	50 miles.	60 miles.
	feet.	inches.	inches.	inches.	inches.	inches.
Waggon with wheels 3 feet in diameter. Width of way, 4·70 feet. Play of waggons, on the railway, on each side, ·5 inch. Inclination of the tire of the wheel, $\frac{1}{7}$.	900	·16	·37	·65	1·02	1·47
	800	·37	·83	1·47	2·30	3·31
	700	·63	1·42	2·52	3·94	"
	600	·98	2·21	3·92	"	"
	500	1·47	3·31	"	"	"

When the outer rail of a curve has this superelevation, it is clear that, if a train of waggons traverse the curve at the maximum velocity for which the superelevation has been calculated, the train will deviate laterally as far as the rise of the flange of the wheel, and will continue its motion in that position to the end of the curve, since the divers forces then applied to the waggon, either to drive it outwards, or to bring it back within the curve, will hold each other in equilibrium. There will be no risk of accident then to fear; but the resistance of the train will be greater than on a railway in a straight line. In effect, the curve traversed will have a radius expressed by ρ, and the rolling cone, formed by the conical inclination of the wheels, will have the radius ρ', which is greater. For the cone to roll of itself along the curve, making the wheels describe distances, unequal in the same proportion as the lengths of the outer and inner rails, it would be necessary, as has

been seen above, that ρ' should be equal to ρ. The dragging of the wheels will therefore take place on the difference between the circumferences described with the radii ρ' and ρ. The parallelism of the axles, besides, will have an effect by so much the greater as the radius of the curve is smaller. The superelevation of the rail, such as we have determined it above, is then to be considered as rendering impossible, in the regular state of things, that the train should be thrown off the rails, and not as destroying all increase of resistance in the passage of curves. Some ingenious means have been proposed to attain this latter result, but as they are not yet sufficiently confirmed by experience, we refer the reader to the publications in which their inventors have developed the advantages to be derived from them.

We will however observe that, in general, the only object of all the modes proposed for passing curves, is to obviate the inconveniences which they offer in the *normal* state of things. But a rail broken or accidentally raised, a stone fallen on the road, an axle or a wheel broken, always present chances of much more serious accidents on curves than on the straight line.

APPENDIX.

EXPENSES OF HAULAGE BY LOCOMOTIVE ENGINES ON RAILWAYS.

To complete the knowledge of locomotive engines, it still remains to consider them with regard to their economy; that is to say, to examine the amount of the expenses attending the haulage by means of locomotive engines on railways. This research will be the object of the present Appendix.

We shall draw the documents we have to present on that subject from the two most ancient enterprises of the kind in England: the Liverpool and Manchester, and the Stockton and Darlington Railways. They will have, besides, the advantage of presenting examples of two very different sorts of conveyance: the one rapid, and principally composed of passengers; the other slow, and consisting of goods.

We shall divide the expenses incident to locomotive engines on railways in the following manner:

The repairing and maintaining of the engines, their consumption of fuel, and the expenses for conducting them, constituting together the expenses for locomotive power, properly so called;

The expenses for the maintenance of the way;

The office expenses and contingencies, which, united

with the preceding, give the total expense of the haulage by means of locomotive engines on railways;

Finally, we shall conclude with a glance at the receipts compared with the expenses, which will show the profits arising from these enterprises, to the companies who carry them into execution.

In treating of these various subjects, throughout this Appendix, we shall give the amount of expenses per *ton gross*, that is, including the weight of the waggon which conveys the goods. This is the most accurate method, since it refers to the effort really exerted by the engines, and to the weight effectively borne by the rails; and it matters little, as regards the engine or the rails, whether in this total weight, a half merely or any other proportion be composed of merchandise or useful weight. It will afterwards be easy, on any line of road, to deduce the cost of conveyance per *ton of goods*, when once, on that line, knowledge is obtained of the weight of the waggon compared with that of the load. In the weight of a loaded waggon, generally, the load is two-thirds, the waggon one-third, which establishes at $\frac{2}{3}$ the ratio of the effective tons, or tons of useful weight, to the tons gross.

Sect. I. *Expense for repairs of locomotive engines.*

Among the expenses just enumerated, that which will naturally first engage our attention is the expense for keeping the engines in repair.

Before we enter into any calculations on that head, it is necessary to mention that what is meant by repairs to the engines, is nothing less than their complete re-construction; that is to say, when an engine goes into repair, unless it be for some trifling accident, it is taken to pieces and a new one is constructed, which receives the same name as the first, and in the construction of which are

made to serve all such parts of the old engine as are still capable of being used with advantage. The consequence of this is, that a re-constructed or repaired engine is literally a new one. The repairs amount thus to considerable sums, but they include to a great extent the renewal of the engines.

According to the Tables at the end of this work, it will be seen that in the year ending on the 30th of June, 1834, the repairs of the engines of the Liverpool Railway cost—

From June 30, to December 31, 1833.		
Materials for repairs	£3,755 3 7	
Workmen	4,401 4 10	
Repairs out of the establishment	613 3 9	
		£8,769 12 2
From December 31, 1833, to June 30, 1834.		
Materials	£4,140 19 6	
Workmen	5,432 8 8	
		9,573 8 2
		£18,343 0 4

The question is now what was the work executed by those engines during that interval? Now, referring to the same Tables which will be found below, it will be seen that the goods conveyed on the line during the year were—

Between Liverpool and Manchester	139,328 t.
On part of the line, making an average of 15 miles,[1] 24,934 t., which, on the whole, is equal to . . .	12,467
Total . . .	151,795 t.

In the Tables just mentioned, there appears indeed some other haulage executed, such as goods for Bolton

[1] The distance to which the Company carries the Wigan and Warrington goods, which form the principal part of this article, is 15 miles.

and coal for several places along the line; but this work is done by engines which do not belong to the Company, so that their repairs are not included in the following reports, and for that reason we do not take it into account in this place.

The above weight is that of the goods conveyed, to which must be added the weight of the waggons. Now, on that railway, the average load carried on a waggon is 3·5 t., and the waggon itself weighs 1·5 t.; so the weight of the carriages that served for the above-mentioned tonnage will be known by multiplying the number obtained, by the ratio $\frac{1 \cdot 5}{3 \cdot 5}$. And as, moreover, the engines, for want of sufficient returning traffic, are obliged to bring back half the waggons empty in one of the two directions, or $\frac{1}{4}$ of the whole, we shall have for the *gross weight* drawn by the engines in the course of the year—

Weight of the goods	151,795 t.
Weight of the corresponding waggons	65,055
Weight of the waggons brought back empty . .	16,264
	233,114 t.

This is the tonnage of the goods, to which must be added that of the travellers. In the course of the year, 415,747 travellers were conveyed from one city to the other in 6570 trips.[2] This makes an average of 64 travellers per train. The coaches required for that number of travellers, including the empty carriages added to each train to be ready for any emergency, are six carriages of the first class, or five of the second.[3]

[2] This is the number of the travellers inscribed in the Company's books. It includes neither the travellers put down nor those taken up on the road, the numbers of which balance each other.

[3] The first-class carriages are glass coaches, containing each 18

The weight of six first-class coaches, including the mail, is	21 t.
The weight of a second-class train of five carriages, including one glass coach, is	12·6

Lastly, for 13 trains of the first class there are 16 of the second. Thus, the average weight of the carriages for every 64 travellers may be reckoned at 16·4 t.

Consequently, the gross weight corresponding to the travellers conveyed was—

415,747 travellers, at 15 per t.	27,717 t.
Corresponding weight of the carriages	107,748
Luggage of the travellers, at 28 lbs. each . . .	5,197
	140,662 t.

Thus the total weight drawn during the year, by the engines belonging to the Company, was—

Gross weight for goods	233,114 t.
Gross weight for travellers	140,662
	373,776 t.

Now we have already shown in this work (Chap. XVII. Sect. VI.) that, taking into account the surplus of resistance caused by the gravity of the train and the engines, on the different inclines of the Liverpool and Manchester Railway, the quantity of work executed in the traction of any load, over the whole extent of the line, may easily be determined by the following expressions:

From Liverpool to Manchester . . $W. = 30{\cdot}79\ M_1 + 262,$

From Manchester to Liverpool . . $W. = 36{\cdot}89\ M_1 + 348,$

in which W figures for the quantity of work executed, expressed in tons gross drawn one mile *on a level*, M_1 the

persons; they weigh 3·65 t. Those of the second class are open, and have 24 places; their weight is 2·23 t. Lastly, the mail-coaches weigh 2·71 t., and carry 10 travellers. Each glass coach has besides one outside place.

load of the engine, in tons gross *exclusive of tender*, and the numbers 262 and 348 the average work caused by the gravity of the engines and their tender, and by the traction of that tender. Taking then a mean between these two expressions, it will appear that the conveyance of a load M_1 from one end of the line to the other, in both directions, will produce a quantity of work expressed by

$$W. = 33{\cdot}84\,M_1 + 305 \text{ tons gross 1 mile on a level.}$$

This premised, as the above 373,776 tons gross were conveyed by the engines in 11,656 trips, it follows that the average load of the engines per trip was 32 tons gross. Substituting then this number for M_1 in the preceding expression, we find that the work done by the engines in each trip was 1387·9 tons gross drawn 1 mile *on a level.* Thus as the engines performed in all 11,656 trips, the total work done by them was

$$11656 \times 1387{\cdot}9 = 16{,}177{,}080 \text{ tons gross drawn 1 mile on a level;}$$

and the ratio of this number to the real conveyance effected, namely, 373,776 tons gross drawn 29·5 miles, or 11,026,392 tons gross drawn 1 mile, shows at the same time that, on that line, the gravity and draught of the tenders increase the work of the engines in the proportion of 1·467 to 1.

For the work above stated, the repairs of the engines cost £18,343 0*s.* 4*d.* This sum, reduced to pence, gives 4,402,324 *d.* Consequently the repairs, per ton gross conveyed 1 mile on a level, amounted to

$$\frac{4402324^d}{15177080} = {\cdot}272^d.$$

To perform this work, the engines made 6570 trips with travellers, that is to say, at a velocity of 20 miles per hour; and 5086 trips, with goods, or at a velocity of 12·5 miles an hour. The average velocity of the haulage was therefore 16·73 miles per hour.

We have said elsewhere that, at the time of these observations, the Liverpool and Manchester Railway Company possessed thirty locomotive engines. It must not be concluded, however, that that number is necessary in order to perform the above-mentioned haulage. Of these 30 engines, about one-third were useless. This third consisted of the most ancient which, having been constructed at the first establishment of the railway, at a time when the Company had not yet obtained sufficient experience in that respect, are found now to be out of proportion with the work required of them. The engines in daily activity on the road amounted to about 10 or 11, and with an equal number in repair or in reserve, the business might have been completely ensured; for the surplus, above that number, was nearly abandoned.

We shall complete what has just been said on the Liverpool and Manchester locomotive engines, by adding a document that will show what these engines are capable of executing in a daily work, and the improvement they have undergone in the course of the last few years, with respect to their construction.

Work done by the ten best locomotive engines of the Liverpool and Manchester Railway, during the years 1831, 1832, 1833, *and the first twelve weeks of* 1834.

Year.	Name of the engine.	Total time the engine has been on the road, either in activity or in repair.	Total distance travelled by the engine.
		Weeks.	Miles.
1831.	Mercury	52	23,212
	Jupiter	44	22,528
	Planet	52	20,404
	Saturn	38	19,510
	Mars	50	18,645
	Majestic	52	18,253
	North Star	52	15,677
	Northumbrian	52	15,607
	Phœnix	52	15,405
	Sun	37	13,434
	Total	481	182,675
	Average per week . .		380
1832.	Vulcan	52	26,053
	Liver	43	22,651
	Venus	52	20,464
	Etna	52	20,399
	Saturn	52	20,312
	Vesta	52	17,739
	Victory	52	17,082
	Planet	52	16,885
	Sun	52	16,535
	Fury	52	15,603
	Total	511	193,723
	Average per week . .		379

Work done by the ten best locomotive engines of the Liverpool and Manchester Railway, during the years 1831, 1832, 1833, *and the first twelve weeks of* 1834.

Year.	Name of the engine.	Total time the engine has been on the road, either in activity or in repair.	Total distance travelled by the engine.
		Weeks.	Miles.
1833.	Jupiter	52	31,582
	Ajax	52	26,163
	Firefly	39	24,879
	Liver	52	23,134
	Pluto	52	20,308
	Vesta	52	19,838
	Leeds	48	19,364
	Saturn	52	18,738
	Venus	52	18,348
	Etna	52	17,763
	Total	503	220,117
	Average per week . .		438
1834.	Firefly	12	8,542
	Vulcan	12	8,526
	Saturn	12	7,290
	Liver	12	7,080
	Sun	12	7,080
	Etna	12	6,557
	Leeds	12	5,712
	Ajax	12	4,890
	Venus	12	4,632
	Pluto	12	4,246
	Total	120	64,555
	Average per week . .		538

As we have already said that the average load of the engines, on this railway, is 32 tons gross, *exclusive of tender*, it would be easy to deduce from this Table, the number of tons gross which have been carried 1 mile by each of the engines during the time of its work. Similarly, by dividing the number of miles travelled by the length of the railway, which is 29·5 miles, we might deduce first, the number of trips performed by each engine; and then, recollecting that each trip, with the average load of 32 tons gross, corresponds to 1388 tons gross drawn 1 mile *on a level* (page 542), we might deduce the number of tons gross drawn 1 mile *on a level* by the engine, either in the course of a year, or during the whole time it was on the line. We will not offer this calculation for each engine, but will give the result of it for those two, among them, which have done the most work.

At the time of the completion of the above Table, the *Liver* had been employed on the railway during 107 weeks, had travelled a distance of 52,865 miles, or drawn 2,487,140 tons gross, tender included, one mile *on a level;* the *Firefly* had worked 57 weeks, had travelled a distance of 33,421 miles, or drawn 1,572,360 tons gross, tender included, one mile *on a level;* the average velocity at which these loads had been drawn was 16·73 miles per hour, and neither of these engines, at the period in question, had yet required a thorough repair.[4]

To give an example of the expense of repairs of locomotive engines, under other circumstances, and with engines of another construction, we will here set down the work performed by the locomotive engines on the

[4] The greater part of these excellent engines were built by Mr. R. Stephenson. The *Liver* engine is the work of Mr. Edward Bury, of Liverpool.

Stockton and Darlington Railway, during the same year, that is to say, from June 30, 1833, to June 30, 1834, and the amount of expenses for repairing those engines during the same space of time.

On this railway, the engines performed, in the course of the year, and descending with their loads, a number of trips which, estimated in trips of 20 miles each, according to the custom of the Company, amounts to 5318·5, or 5119 trips of 20·78 miles each; and this necessarily carries with it an equal number of trips in ascending with the empty waggons. The load of the engines at each trip going down, is 24 waggons, carrying 63·6 tons effective of coal, and weighing in tons gross 94·8 tons. In bringing the 24 empty waggons up again, the load of the engines is 31·2 tons gross. Recurring to the expression which we have given Sect. VI. Chapter XVII., of the work done in conveying a given load on the whole extent of this railway, it will readily be perceived that, considering the bringing back of the waggons empty, every trip descending corresponds to the draught of 2650 tons gross 1 mile on a level; and consequently the total work executed in the year on this railway, amounts to

13,565,350 tons gross, one mile on a level.

With regard to the corresponding expenses, it is to be noted that, after having for a long while kept and repaired their engines themselves, the Directors of the Stockton and Darlington Company decided, in order to avoid minute accounts, to do all that work by contract; and, in consequence, in 1833, they put their engines into the hands of three persons. By the contract entered into, the Company paid $\frac{4}{10}$ of a penny per ton of *goods* carried one mile; and, for that price, the contractors undertook, not only to keep the engines in good repair, furnishing workmen and materials, but also to pay all the current expenses of haulage, such as salary of the engine-

men, fuel, oil, grease, &c.; and to pay moreover to the Company an interest of five per cent. on the capital representing the value of the engines, and of all the establishments placed at the contractors' disposal for their work.

The total sum paid to the contractors by the Company for that object during the year ending June 30, 1834, was

£11,347 1*s.* 9*d.*;

and deducting the expenses for rent, interest of capital and haulage, the amount of which is known, the Directors of the Company reckon that the definitive sum remaining with the contractors for the repairs of the engines (bars of fire-box included), amount, with the general profit on the whole bargain, to

£5,732 18*s.* 5*d.*

This sum, reduced to pence, gives

1,375,901*d.*

It was expended for the carriage of 13,565,350 tons gross one mile on a level; so that finally the expense, per ton gross carried one mile on a level, including the profits on the bargain, amount to

0·101*d.*

As a complement to what we have said, and to show, on this railway as well as upon the Liverpool one, the work the engines are able to perform, we shall give a Table of the haulage executed, and repairs done to the engines, during five months of the year 1833.

To form, in this Table, the column which contains the work done, in tons gross carried 1 mile *on a level, tender included*, the number of tons of coal carried 1 mile descending is multiplied by 2; because, from the calculation indicated page 547, the conveyance of a load of 63·6 tons of coke, along the whole line, or the distance of

20·78 miles, corresponds, including the return of the empty waggons, the gravity, &c., to a quantity of work expressed by 2650 tons gross drawn 1 mile *on a level;* and that this number is double the product $63{\cdot}6 \times 20{\cdot}78 = 1322$, which represents the useful work done at each trip, or the number of tons of coal carried 1 mile by the engine.

The last column but one of the Table contains the amount of expenses for keeping each engine in repair during the time it was on the line, and the last column contains the same expenses divided per ton gross drawn 1 mile on a level; but we must add that, at the time when this Table was formed, there were, among the engines of the railway, twelve completely new. Besides, the amount of repairs here set down includes only the workmen's wages, and not the materials, those materials having been purchased largely and kept in store. It is therefore subjected to these restrictions, that we present the following Table.

Most of the engines of the Stockton and Darlington Railway were built by Mr. T. Hackworth, of Brusselton, near Darlington.

Statement of the work done by the locomotive engines on the Stockton and Darlington Railway, from July 1, to December 1, 1833.

Number of the engine.	Name of the engine.	Number of days that the engine was In activity.	In repair.	Total number of miles travelled by the engine.	Tons of coals carried to one mile going down, by the engine.	Gross tons carried to one mile on a level, including the waggons and return.	Amount of the repairs made to the engine during that time. £.	s.	d.	Amount of the repairs per gross ton carried to 1 mile on a level.	Observations.
		days.	days.	miles.	tons.	tons.	£.	s.	d.	d.	
1	Locomotion.	80	52	5,300	146,011	292,022	41	19	7	·035	Boiler with a flue and two returning tubes.
2	Hope.	63	69	3,100	82,305	164,610	57	5	5	·084	—— with a single flue.
3	Black Diamond.	27	105	1,000	26,920	53,840	14	0	5	·062	—— with a single flue.
4	Diligence.	2	130	80	1,906	3,812	13	18	3	·877	Engine taken to pieces.
5	Royal George.	11	121	700	23,733	47,466	161	7	8	·816	Boiler with a flue and one returning tube.
6	Experiment.	70	62	4,400	122,442	244,884	53	1	2	·052	ditto
7	Rocket.	64	68	3,940	109,512	219,024	57	0	9	·062	ditto
8	Victory.	107	25	10,600	349,150	698,300	58	3	10	·020	ditto
9	Globe.	60	72	3,120	70,683	141,366	36	4	6	·061	Boiler with 120 returning tubes.
10	Planet.	27	105	1,200	20,429	40,858	53	7	5	·314	—— with 88 ——
11	North Star.	55	77	2,400	47,546	95,092	32	5	10	·082	—— with 88 ——
12	Majestic.	47	85	2,880	90,422	180,844	131	2	3	·175	—— with 104 ——
13	Coronation.	52	80	2,940	97,687	195,374	46	16	2	·057	—— with 104 ——
14	William IV.	55	77	4,060	134,440	268,880	78	19	8	·071	—— with 104 ——
15	Northumbrian.	59	73	4,480	143,885	287,770	67	14	11	·056	—— with 104 ——
16	Director.	91	41	5,860	202,492	404,984	107	19	11	·064	Boiler with tubes, Napier's patent.
17	Lord Brougham.	62	70	4,780	155,729	311,458	62	5	10	·048	Boiler with 104 returning tubes.
18	Shildon.	63	22	4,720	159,400	318,800	49	16	3	·038	—— with a flue and two returning tubes.
19	Darlington.	88	44	6,180	200,110	400,220	45	0	6	·027	—— with a flue and two returning tubes.
20	Adelaide.	71	61	3,700	126,390	252,780	90	11	7	·086	—— with 104 returning tubes.
21	Earl Grey.	110	22	7,960	276,462	552,924	14	19	6	·007	—— with a flue and two returning tubes.
22	Lord Durham.	84	48	6,480	213,737	427,474	67	13	8	·039	—— with 104 returning tubes.
23	Wilberforce.	55	9	4,200	141,534	283,068	51	17	11	·044	—— with 104 returning tubes.
	Total	1403	1518	94,080	2,942,925	5,885,850	1393	13	0	·057	

SECT. II. *Expense of Fuel.*

We have already, in Chapter IX. of this work, related experiments from which may be deduced the consumption of fuel according to the load the engines have to draw. However, as in the intervals of the trips, the fire must be kept up, and as, besides, there are always unavoidable losses during the work, an increase of expense in that respect must naturally be expected in practice. This we also learn in a positive manner by the examination of facts.

According to the half-yearly reports of the Liverpool Railway Company, for the year ending June 30, 1834, the expense for fuel for the locomotive engines was

£6,079 15*s*. 8*d*.

The number of trips performed was 11,656: consequently the expense for fuel for each journey amounted to 10·432*s*.; and as the average price of coke used during that year on the railway was 23·5*s*., the consumption of fuel, measured in weight, amounted to 994·37 lbs. per trip. Now we have already seen that the average load of the engines, during the year, was 32 tons gross. A load of 32 tons, not including the tender, consequently required, by the fact, a consumption of coke of 994 lbs. Thus, as the work corresponding to the conveyance of that load from one end of the line to the other is equivalent to 1388 tons gross carried 1 mile *on a level* (page 542), it is plain that the consumption of fuel amounted to

·716 lb. of coke per ton gross carried 1 mile on a level;

and from the price of coke on that line, that consumption cost

·090*d*. per ton gross carried 1 mile on a level.

Our special Experiments given Chapter XI. only give an average consumption of 784 lbs. of coke for a load of

32 tons. By this it will be seen that, in practice, and with the nature of the business on that line, the different losses amount to one-fourth of the expense of the active work. This considerable increase is owing not only to the necessary expense for lighting the fire every morning, but also to the necessity, on that line, of keeping, for the passage of the inclined planes, helping engines, the fire of which must remain alight the whole day, although they only serve at distant intervals; to the number of trips which the engines make almost without load; and in fine, to the long delays between one journey and another. These circumstances, that of the helping engines alone excepted, are inevitable in a business of the nature of that of the Liverpool and Manchester Railway.

On the Stockton and Darlington Railway the same causes of loss do not exist, at least not to the same degree.

According to the notes, carefully kept by the Directors of that Company to serve as a foundation to the contracts they sign, the quantity of coal consumed on an average, during one journey of an engine, that is to say, to convey 24 loaded waggons a distance of 20 miles down hill, and bring them back again empty to the same distance up hill, costs the engine-men 4*s.* 9¾*d.*, when the coals are at 5*s.* per ton. So the weight of coals consumed is 2157 ℔s.

Now we have seen that the work done in one trip is equivalent to 2650 tons gross drawn 1 mile on a level; the consumption of coal per ton gross carried 1 mile on a level is therefore

·814 ℔.,

or, from the price of the fuel,

·0218 *d.*

This is nearly the same consumption in weight as on the Liverpool and Manchester Railway. The result may

appear surprising; for the boilers of the Darlington engines are generally constructed on a less economical principle, as to the application of heat, than the Liverpool ones; but considering the work of each line, this circumstance will easily be accounted for. On the Darlington Railway the engines never go off but with a full load; that is to say, that, taking the two trips together, the descending and the ascending, the engines draw, as has been shown, an average load of 63 tons gross per trip, which circumstance we know to be favourable to the expenditure of fuel. If these engines drew only an average load of 32 tons, like the Liverpool ones, their relative consumption would certainly be greater. To this must also be added that, on the Darlington Railway, the engines suffer no delay between their trips.

It is to these combined circumstances that the practical result appearing in this case must be attributed. As railways for goods are generally found to have these advantages over railways for travellers; that is to say, as less frequent departures admit of starting the engines more completely loaded and with less loss of time between the trips, it ought to be considered that the comparative saving of fuel which we notice, originates in the very nature of the work itself.

SECT. III. *Expense of locomotive power.*

To the expenses just noted, namely, the repairs of the engines and the fuel, are to be joined several accessory charges for the conducting of the engines, such as enginemen's and assistants' wages, oil, grease, hemp, &c. The amount of these divers objects taken in their detail, is reported in the Tables of receipts and expenses of the Liverpool and Manchester Railway, which will be given

farther on; but it is necessary to consider them here taken collectively.

These charges, together with the expenses for repairs of the engines and the expenses for fuel, constitute the expenses of *locomotive power*, properly so called. It is then indispensable to include them in the calculation, in order to know the definitive cost of locomotive engines used as a means of conveyance.

It will be seen in the Tables of detail given farther on, that on the Liverpool and Manchester Railway the expenses of locomotive power amounted, during the year under consideration, to the sum of

£29,607 5*s.* 11*d.*

As we have seen that the work done by the engines amounted to 16,177,080 tons gross, drawn one mile (page 542), it follows that the expenses for locomotive power, were

·439*d.* per ton gross per mile on a level, at an average velocity of 16·73 miles per hour.

On the Stockton and Darlington Railway, we have said that the Company passed a contract for the locomotive power, and that the total price paid to the contractors during the year was

£11,347 1*s.* 9*d.*

Out of this sum the contractors pay to the Company, for rent of work-shops, and interest of capital vested in engines,

£824.

There remains, then, definitively paid for locomotive power,

£10,523 1*s.* 9*d.*;

and as this sum has defrayed the conveyance of 13,565,350 tons gross to 1 mile (page 547), the rate of that expense was

·186*d.* per ton gross per mile on a level, at the speed of 8 miles per hour.

This expense, however, refers to coal used as fuel. As this circumstance does not occur on the railways recently formed, and particularly on the Liverpool and Manchester Railway, it will be necessary, in order to have prices comparable between them, to take into account the difference of price of the two fuels.

Now, the Darlington Company burn ·814 lb. of coal per ton gross per mile on a level. Supposing in the two kinds of fuel an equal power of producing heat, the consumption of coke would also be ·814 lb., and taking that fuel at the Liverpool price, namely, at 23*s.* 6*d.* per ton, the expense per ton gross conveyed one mile would be ·102*d.*, instead of ·022*d.*, which it actually is. There would then be an augmentation of expense per ton gross, per mile, of

·080*d.*

Thus, with the use of coke instead of coal on the Stockton and Darlington Railway, the expense for locomotive power would amount in this year to

·266*d.* per ton gross per mile on a level, at the average velocity of 8 miles per hour.

It will be remarked that this expense, compared with that of the Liverpool and Manchester Railway, for the same object, is within a very little in proportion to the velocity on each line, namely, 8 miles per hour in one case, and about 17 miles per hour in the other: this is a point which we shall again touch upon farther on.

Sect. IV. *Expense for maintenance of way.*

The expenses for keeping the Liverpool and Manchester Railway in repair, during the year under con-

sideration, from June 30, 1833, to June 30, 1834, were, according to the Tables of detail given hereafter,

£15,776 12*s.* 1*d.*

During the same time the following weights passed on the railway, drawn either by the Company's engines, or by engines belonging to other companies, namely:

Goods on the whole road	139,328 *t.*	
—— on half the road 24,934 tons, making on the whole road	12,467	
—— between Bolton, and Manchester or Liverpool, 38,341 tons, or on the whole road . . .	19,170	
Coal on half the line 86,173 tons, or on the whole .	43,086	
Corresponding waggons, $\frac{1 \cdot 5}{3 \cdot 5}$ of the weight of the goods	128,431	
Waggons brought back empty, ¼ of the whole . .	32,108	
Total for goods and coal		374,590 *t.*
Coaches, travellers, and luggage, as above . .		140,662
		515,252 *t.*

Thus 515,252 tons gross passed over every mile of the railway, exclusive of the weight of the engines and their tender. The expenses for maintenance of way having been £15,776 12*s.* 1*d.* for 31 miles, the whole length of the railway, or £508 18*s.* 5*d.* per mile, they amount to

·237*d.* per ton gross per mile.

On the Stockton and Darlington Railway, during the same year, the expenditure for repairs of the road was as follows:

	£	*s.*	*d.*
Workmen's wages for repairs to the railway . .	5,320	5	0
Materials for ditto	2,578	3	8
Repairs to bridges	69	17	7
Repairs to walls and fences	280	7	11
Contingencies	467	3	7
	8,715	17	9

And deducting the charges relative to walls and fences, which are not included in the preceding article for the Liverpool and Manchester Railway, as may be seen in the detailed accounts presented farther on, the amount of this expenditure reduces itself to

£8,435 9*s.* 10*d.*

On the other hand, the weights which passed on the railway, drawn either by locomotives or by the stationary engines or by horses, were:

		tons to 1 mile.
375,320 tons of coal, equal in tons carried one mile, to	8,526,904 *t.*	8,858,193
32,996 tons of lime-stone	133,064	
17,387 tons of goods	198,225	
6,499 tons in passengers, equal to		53,733
Waggons, $\frac{1 \cdot 30}{2 \cdot 65}$ of the weight of the goods conveyed		4,345,529
Waggons brought back empty, same weight		4,345,529
Weight of coaches, in tons carried one mile		161,199
	Total	17,764,183 *t.*

The expense per ton gross per mile, exclusive of the weight of engine and tender, amounts then to

·114*d.* per ton gross per mile.

Taking the repairs of walls and fences into the account, this article would give ·118*d.* per ton gross per mile.

It must be observed that this expense, as well as that above mentioned for the Liverpool and Manchester Railway, is rather higher than it will be on an average for the years to come, on account of an extraordinary replacing of the rails of both lines, by other rails of much greater strength.

The expenses for keeping in repair the Stockton and Darlington Railway would unquestionably be less, if the waggons used on that line were on springs, like those of the Liverpool and Manchester Railway. In the present state of things, however, those expenses scarcely amount to half the expenditure of the Liverpool and Manchester

Railway for the same object; that is to say, they are, as well as the expenses for locomotive power, very nearly in proportion to the velocity on each line.

It must not however be thought that the great difference observed in this respect between the two railways, is exclusively owing to the velocity of the motion. That velocity, indeed, constitutes much of it, but the conditions attending each sort of business have a no less considerable influence. What we mean is, that the conveyance of passengers forming the chief business on the Liverpool and Manchester Railway, their safety requires that much more care be taken of the engines than when the load is composed only of coal, as on the Stockton and Darlington Railway. The consequence is, that the Liverpool engines are kept with a degree of care, we might even say of luxury, to which the Darlington ones can by no means be compared. To explain our idea completely, we may say that the business of the Darlington Railway is a business of waggonage, and that of the Liverpool Railway a business of stage coaches.

The *data* laid down above must therefore be taken each in their speciality, that is to say, the one as suitable to a slow motion, with engines of a certain construction and intended for the draught of goods, and the other to a rapid motion with engines of a different construction, and intended for the draught of passengers, for which the former would be unfit.

Before we close this article, we must remark that the repairs of the railway consist principally in replacing the blocks, chairs, keys, and pins. The rails themselves, being of malleable iron, seldom break. As for their gradual decrease of weight, by wear, that is a very inconsiderable effect, as may be seen by the following fact.

On May 10th, 1831, on the Liverpool and Manchester Railway, a malleable iron rail, 15 feet long, carefully cleaned, weighed 177 lbs. 10½ oz. On February 10th, 1833,

the same rail, taken up by Mr. J. Locke, then resident engineer on the line, and well cleaned as before, weighed 176 lbs. 8 oz. It had consequently lost in 21 months a weight of 18½ oz. The number of tons gross that had passed on the rail during that time was estimated at 600,000. Thus we see that with so considerable a tonnage, and with the velocity of the motion on that railway, the annual loss of the rail was only $\frac{1}{268}$ of its primitive weight. So that it would require more than a hundred years to reduce it to the half of its present strength.

Sect. V. *Total expense of haulage.*

So far we have seen to what rate per mile the expenses amount for locomotive power and for maintenance of road. But to determine the definitive rate of the expenses of all kinds, necessary for working railways by means of locomotive engines, it still remains to make the same calculation for each of the other expenses incident to these engines on the railway.

Taking each of these charges from the detailed Tables of the Liverpool and Manchester Railway Company, and dividing it according to the respective work to which each refers, we arrive at the following result:—

Partition of the expenses of haulage on the Liverpool and Manchester Railway.

£.	s.	d.		Expense per ton gross per mile. Travellers.	Goods.
15,971	13	6	Repairs to coaches, compensation for luggage lost, offices for booking passengers; to be divided according to a gross tonnage, for travellers, of 140,662 tons (page 541) and for a length of road of 30 miles, makes	·90837^{d}	„
25,270	7	1	Loading of goods, compensation for ditto, cartage in the towns of Liverpool and Manchester, loading and unloading of coals; to be divided according to 374,590 tons gross of goods and coals (page 556) and for 31 miles of road, makes	„	·52235^{d}
10,686	10	4	Interest on borrowed capital	„	„
29,607	5	11	Locomotive power already divided (on the level)	·43925	·43925
15,776	12	1	Maintenance of way already divided	·23705	·23705
2,294	6	8	Stationary engine and tunnels; to be divided according to 515,252 tons gross (page 556) and for 31 miles, makes per ton gross per mile	·03447	·03447
3,462	15	5	Repairs to waggons; to be divided according to 233,114 tons gross drawn to 31 miles (page 540) makes	„	·11500
13,373	6	8	Direction, offices, engineers, law expenses, police, rent, taxes, rates, repairs to walls and fences, and petty expenses; to divide (page 541) according to 373,776 tons gross and for 31 miles, makes ..	·27700	·27700
116,442	17	8	Total per ton gross per mile on a level	1·89614^{d}	1·62512^{d}
			And consequently:		
			Total expense per traveller per mile on a level, (page 541) $1{\cdot}89614 \times \frac{140662}{415747}$ ..	·64153	
			Total expense per *effective* ton of goods per mile on a level, (page 540) $1{\cdot}62512 \times \frac{5}{3{\cdot}5}$	„	2·32160

Though each of these expenses is here divided in proportion to the tonnage and to the length of the road, it is understood that there are several among them which would suffer no change, were the road longer or shorter. Such are the charges for loading, cartage, offices, &c. Account then should be taken of this circumstance, were it desired to deduce from the data of the Liverpool and Manchester Railway, what would be the expenditure on a different line.

According to what has already been said of the effects of the velocity on the repairs of the engines and maintenance of the road (Sect. III. and IV. of the Appendix), it may be observed that the trains of waggons, moving slower than those of coaches, ought not, at equal weights, to cause the same wear and tear of the engines, nor the same repairs to the road. As experience seems to indicate that these effects are, for an equal tonnage, in direct proportion to the velocity, we shall here take account of this circumstance by separating first the expenses for locomotive power and maintenance of way, each into two portions, in the ratio of the tonnage and of the velocity on each of the two railways; and it will not be till after this first partition, that we shall perform the division of each portion per ton per mile, as above. This calculation gives the following results:—

Partition of the expenses of haulage on the Liverpool and Manchester Railway, taking into account the difference of velocity of the trains.

	Expense per ton gross per mile. Travellers.	Goods.
Locomotive power: £29,607 5*s.* 11*d.*, divided on a tonnage of 140,662 tons gross drawn at the velocity of 20 miles an hour, for the travellers, on one part;—and 233,114 tons gross of goods drawn at the velocity of 12·5 miles per hour, on the other part (pages 540 and 541);—makes:		
For travellers £14,543 7*s.* 11*d.*, or per ton gross per mile, *on a level* (page 542)	·57334^{d}	„
And for goods £15,063 18*s.* 0*d.*, or per ton gross per mile, *on a level* (page 542)		·35834^{d}
Maintenance of way: £15,776 12*s.* 1*d.*, divided on a tonnage of 140,662 tons gross drawn at the velocity of 20 miles an hour for the travellers, on one part;—and 374,590 tons gross of goods drawn at the velocity of 12·5 miles per hour, on the other part (page 556);—makes:		
For travellers £5,921 5*s.* 1*d.*, or	·33676	„
For goods £9,855 7*s.* 0*d.*, or		·20369
Cartage and expenses of all kinds, above specified, and divided (page 560)	1·21984	·94882
Total per ton gross per mile on a level	2·12994^{d}	1·51085^{d}
And consequently:		
Total expense per traveller per mile on a level (see preceding Table, page 560)	·72063	„
Total expense per *effective* ton of goods per mile on a level (see preceding Table)		2·15830

With these results, an exact account may now be rendered of the profits arising from each kind of business. In effect, the gross receipt, for travellers, during the year, was

£105,456 3*s*. 10*d*.,

and the number of passengers conveyed from one end of the line to the other, a total distance of 30 miles, for the passengers, was 415,747. Thus the receipt per passenger per mile is

2·029*d*.

We have just seen that the Company disburses for the same conveyance per mile, *on a level*, ·7206*d*.; and dividing the disbursement per *current* mile of the railway, (not on a level,) there would result, for this expense,

·807*d*.

The net profit per passenger per current mile is therefore

1·222*d*.

Again, taking the goods separately, the receipt for them is found to be

£81,045 6*s*. 1*d*.;

and as the work done is 151,795 effective tons carried the distance of 31 miles, as far as the port, the gross receipt per ton of goods per mile was

4·153*d*.:

deducting, for the expenditure per *current* mile, relative to the same article,

2·385*d*.,

there remains a net profit, per ton of goods per current mile, of

1·768*d*.

We here see that, when the engines draw an effective ton composed of 15 passengers, they yield a net profit of

18·330*d.*; and that, in drawing the same weight of goods, the net resulting profit is but 1·768*d.*, or the tenth part of the former.

This proves that on lines established on the system of the Liverpool and Manchester Railway, the chief profit is to be expected from travellers; and it would be a self-deception to reckon principally on the produce of the goods. Such a result indeed was to be foreseen from the consideration that, at the average price of places in the coaches, 15 passengers pay to the Company, for the trip between Liverpool and Manchester, the sum of 68 shillings, whereas the conveyance of a ton of goods is paid only at the rate of 10 shillings and some pence for the same distance.

From what has already been said of the maintenance of the engines and of the road, on the Stockton and Darlington Railway, it will readily be conceived that the total expenses of haulage are much less on that line than on the Liverpool and Manchester Railway. They are usually quoted, approximatively, as amounting to one penny per ton of coal carried 1 mile in the direction of the trade; but as the draught in the direction of the trade, on an inclined line, does not give a precise idea of the effort exerted, it will be proper here to make the calculation in the same way as has been done for the Liverpool and Manchester Railway.

The Company's accounts are divided under three principal heads, namely: locomotive power, maintenance of way, and offices.

The first comprises charges of all kinds for repairs of engines, engine-men's and assistants' wages, fuel, oil, grease, hemp, and other articles of daily consumption for conducting the engines and trains. The second includes workmen and materials for repairs to the road, new rails,

draining, ballasting, repairs to bridges, walls, and fences, and incidental expenses of the same nature. Lastly, the office expenses include stationery and printing, clerks, law disbursements, taxes, rates, police, and contingencies.

We have already seen that during the year from 30th June, 1833, to 30th June, 1834, the expenses for locomotive power amounted to ·186*d.* per ton gross per mile on a level (page 555); those for maintenance of way, including the repairs to walls and fences, were ·118*d.*, as was also proved above (page 557). There remain then only the office expenses, which, as will be seen, amount, per gross ton per mile, to ·037*d.*

Consequently, these three articles united give the total expense of haulage per ton gross per mile, on a level, at the velocity of 8 miles an hour, on the Stockton and Darlington Railway, during that year:

Locomotive power	·186^d
Maintenance of road	·118
Office	·037
Total	·341

As however the Company's expenses, that year, were somewhat diminished by the circumstance that twelve of the engines were then nearly new, we here subjoin the same Company's expenses in the year following, in order to compare them with those of the Manchester and Liverpool Railway.

From 30th June, 1834, to 30th June, 1835, these expenses rose to the following rates:

Locomotive Power.

Expense per ton of goods or coals, drawn 1 mile in the direction of the trade, from the Company's accounts, ·41830^d; makes per ton gross per mile on a level, (page 549) $\frac{\cdot41830^d}{2}$ . . . . ·20915^d

Maintenance of Road.

Expense per ton of goods or coals, drawn 1 mile, from the Company's accounts, ·20707^d; makes, per ton gross per mile, considering the weight of the waggons and their return empty, (page 557),

$\cdot 20707 \times \frac{2\cdot 65}{5\cdot 25}$ . . . . ·10452

Office.

Expense per ton of goods or coals, drawn 1 mile, from the Company's accounts, ·07340^d; makes per gross ton per mile, according to the same proportion as above . . . . ·03705

Total per ton gross per mile on a level . . ·35072^d

And per *effective* ton per mile on a level, on a railway without return of waggons empty (page 557),

$\cdot 35072 \times \frac{3\cdot 95}{2\cdot 65}$ . . . . ·52277

These expenses do not include the repairs to the waggons nor the expense for loading them, because the waggons on this line belong to the coal-mine proprietors, who bring them, moreover, to the railway all loaded and ready to start. It will be proper then to add here the former of those articles, on which the Company has conserved some data.

When the Stockton and Darlington Railway Company let out waggons, which it did till near the end of the year 1834, their repairs were found to amount to $\frac{1}{16}$ of a penny, or ·0625*d.* per ton of goods carried 1 mile, or, considering the weight of the waggons and their return empty, to $\cdot 0625^d \times \frac{2\cdot 65}{5\cdot 25} = \cdot 032^d$ per ton gross per mile. They cost the coal-mine proprietors still less: some of these have entered into a contract, on that account, at the rate of 15 shillings a year per waggon. Each waggon is reckoned to

make, on an average, two trips a week or 104 trips of 20 miles each in a year, with a load of 2·65 tons. This bargain then makes the expense no more than ·033*d.* per ton of coal, or ·017*d.* per ton gross per mile; but we will abide by the rate resulting from the Company's books.

Moreover, we have seen that to render the expenses of the Stockton and Darlington Railway comparable with those of the Liverpool and Manchester Railway, an addition must be made to the former, representing the use of coke instead of coal. And finally, among the Liverpool expenses we are to take only those which occur on the Darlington Railway; which will exclude the articles of loading, cartage, and tunnel. With these alterations then, and taking for the Darlington Railway, the expenses of 1834, the comparable expenses of the two railways are as follow:

Total expense for haulage of goods on railways.

Designation of the articles of expense.	Expenses per ton gross of goods per mile, on a level.	
	On the Liverpool Railway, at the velocity of 12·5 miles per hour.	On the Darlington Railway, at the velocity of 8 miles per hour.
Locomotive power	·358*d*	·209*d*
Addition for coke instead of coal .	„	·080
Maintenance of way	·204	·105
Repairs to waggons	·115	·032
Offices	·277	·037
Total	·954	·463
Loading, cartage, &c.	·522	„
Stationary engines and tunnels, &c.	·034	„
Total	1·510	„

It has already been observed that on the Stockton and Darlington Railway the waggons are not kept with the same degree of neatness as on the Liverpool and Manchester line. They are used only for the carriage of coal, which admits of their being employed in any state. They are constructed too with much less nicety, their cost price being but from £17 to £18, instead of £30 or £36, which those of Liverpool cost. Nor is the same expense bestowed on the police of the road, and on divers accessory objects. But as on a railway for slow motion, destined to the conveyance of things of small value, less care is necessary, it may be considered that, under the same circumstances, the same expenses are to be calculated upon.

Thus, recapitulating what precedes, with regard to the total expenses of working railways at great velocity, with simultaneous conveyance of passengers and goods, and railways at small velocity destined to the carriage merely of materials of little value, it appears that on the former the expenses of conveyance for passengers will be ·721*d.* per passenger per mile on a level, and that the carriage of goods, exclusive of loading, cartage, &c., may amount to ·95*d.* or about 1 penny per ton gross per mile on a level; but if the line is exclusively destined to the carriage of goods, or rather to mine-work, it will be possible to perform the conveyance of 1 ton 1 mile on a level, exclusive of loading, cartage, &c., for ·46*d.*, or about ½ penny, that is, for half the preceding sum.

Besides these expenses, which refer to the haulage properly so called, the loading, cartage, &c., may occasion an additional expense of ·56*d.* for every ton gross set in motion, as is seen by the Liverpool and Manchester Railway, which has furnished us with this amount.

SECT. VI. *Of the expense of horses employed as a moving power.*

Having shown the difference of expense existing between the two modes of conveyance mentioned above, it will perhaps be well to say a word here upon the use of horses. This mode of conveyance being easy to establish, may in certain circumstances be useful.

On the Stockton and Darlington Railway, where horses were the moving power for many years, and were still so in 1834, simultaneously with the locomotive engines, the contract passed by the Company, for the hire of horses with their drivers, on the principal line, was but for $\frac{1}{2}$ penny per ton of goods or coal conveyed 1 mile in the direction of the traffic.

To know the price resulting from this, *per ton gross on a level*, it must be remembered that one half of the Stockton and Darlington Railway consists of descents more inclined than the angle of friction, and that the other half is sensibly level. It follows that through half the way the horses have absolutely nothing to draw, and that through the other half they have only to exert the regular draught required by the same train on a level.

Such is the work the horses have to perform in descending the line with the loaded waggons. But moreover and included in the same price, they have to convey back the empty waggons up the line, that is to say, up an average inclination of $\frac{1}{386}$. This work, by reason of the gravity on the plane, is nearly double that of drawing the same empty waggons on a level.

Upon this line, then, the haulage of a waggon of goods 1 mile requires, in consideration of the inclination and returns, the following traction:

1 loaded waggon, namely, 2·65 tons of goods descending one mile, makes, including the waggon, 3·95 tons gross carried $\frac{1}{2}$ mile on a level, or 1·97*t.* carried 1 mile	1·97*t.*
The same waggon, weighing 1·30*t.*, brought back empty up a plane inclined $\frac{1}{288}$, equals, by reason of the gravity, 3 tons conveyed the same distance on a level	3·00
Tons gross carried to 1 mile	4·97*t.*

Consequently the traction of 2·65 tons of goods one mile descending, produces a definitive traction, to the same distance on a level, of 4·97 tons, or 1·88 times as much. The proportion is less here than in the case of locomotive engines, because the weight is less by that of the engines and their tenders.

Since the price paid for the hire of horses is ·50*d.* for the conveyance of 1 ton of goods 1 mile, it follows that the locomotive power per ton gross per mile, on a level, amounts to $\frac{\cdot 50^d}{1\cdot 88} = \cdot 267^d$.

Consequently, adding the other articles above, we have for the total expense of haulage relative to the use of horses as a moving power:

Hire of horses and drivers, or locomotive power . . .	·267^d
Maintenance of the road, as above	·105
Offices, as above	·037
Repairs to waggons, as above	·032
Total per ton gross per mile on a level, exclusive of loading, &c.	·441^d
And per effective ton per mile on a level, $\cdot 441^d \times \frac{3\cdot 95}{2\cdot 65}$	·657^d

We perceive that these expenses are more considerable than those of the Stockton and Darlington Railway locomotive engines, with the use of coal, but nearly equal to what would be necessary with the same engines, if coke were used.

Sect. VII. *Of the net profits.*

Before we pass on to the specified statements of the receipts and expenses of all sorts of the Liverpool and Manchester Railway Company, we shall take down here, from those same statements, the amount of the profits made by the Company, from the opening of the railway. This sketch will show that, if the mode of haulage in question necessitates considerable expenses for its establishment, the profits it produces are fully adequate to indemnify speedily the Shareholders.

The road was opened to trade on September 16th, 1830, and from that period the dividends per share of £100 sterling amounted to the following sums:

December 31, 1830	£2	0	0
June 30, 1831	4	10	0
December 31, 1831	4	17	8
June 30, 1832	4	4	8
December 31, 1832	4	8	0
June 30, 1833	4	7	6
December 31, 1833 (besides a reserved fund of £4,088 8*s*. 10*d*.)	4	15	3
June 30, 1834	4	15	2
Total Sum from Sept. 16, 1830, to June 30, 1834, or in three years, nine months and a half	£33	18	3

This sum makes 9 per cent. per annum, notwithstanding the reserved fund set apart by the Company, and the extraordinary expenses inevitable at the outset of an undertaking, which being the first of its kind, was necessarily obliged to pay dearly for its own experience, whilst future Railway Companies will have only to profit by the experience acquired by their predecessors.

Besides this high interest for the capital invested, the shares of this railway, from the original price of £100

sterling, had risen, after four years' establishment only, to £210; and have since been continually rising: and those of the Stockton and Darlington Railroad bring in 8 per cent. interest, and have risen in the short interval of 9 years from £100 to £300.

These plain facts make it unnecessary for us to add any reflections.

We shall be happy if the elucidations already given with regard to expense, be of use to persons who may feel inclined to engage in these speculations, which cannot fail to be as advantageous to their private fortune as to the prosperity of the country at large. But, to render this part of our subject more complete, we shall conclude this Appendix by giving the specified statements of the receipts and expenditure of the Liverpool and Manchester Railway Company, from its origin, in September, 1830, till the 30th June, 1834, at which period the Directors ceased to render *detailed* accounts to the Shareholders.

EXTRACTS

FROM THE

REPORTS OF THE DIRECTORS OF THE LIVERPOOL AND MANCHESTER RAILWAY,

FROM THE

Opening of the Railway, on the 16*th September*, 1830, *to the* 30*th June*, 1834.

STATEMENT OF EXPENDITURE ON CAPITAL ACCOUNT.

Amount of expenditure on the construction of the way and the works, from the commencement of the undertaking to 31st December, 1833	£1,089,818	17	7

ANNUAL OR WORKING ACCOUNT.

FROM 16TH SEPTEMBER TO 31ST DECEMBER, 1830.

Net profits of the Company	£14,432	19	5
Dividend per share of £100	2	0	0

HALF-YEAR ENDING 30TH JUNE, 1831.

Net profits of the Company	£30,314	9	10
Dividend per share of £100	4	10	0

HALF-YEAR ENDING 31ST DECEMBER, 1831.

	Tons.
Merchandise between Liverpool and Manchester	52,224
Road traffic	2,347
Between Liverpool and the Bolton junction	10,917
Coal from Huyton, Eltonhead, and Haydock collieries, brought by the Company's engines	7,198
Coal from Hulton brought by the Bolton engines	1,198

Number of passengers booked at the Company's offices	256,321
Number of trips of 30 miles performed by the locomotive engines with passengers	2,944
Do. with goods	2,298
Do. with coals	150

Receipts.

	£	s.	d.	£	s.	d.
Coach department	£58,348	10	0			
General merchandise	30,764	17	8			
Coal department	695	14	4			
				£89,809	2	0

Expenses.

	£	s.	d.	£	s.	d.
Office establishment	£902	3	10			
Coal disbursements	60	15	5			
Petty ditto	110	0	5			
Cart ditto	60	17	8			
Maintenance of way	6,599	12	6			
Charge for direction	297	19	0			
Coach office establishment	589	5	9			
Locomotive power	12,203	5	6			
Advertising	59	3	4			
Interest	2,737	7	3			
Rent	900	5	3			
Compensation (coaching department)	156	7	5			
Engineering department	625	0	0			
Carrying disbursements	10,450	12	3			
Taxes and rates	2,763	5	1			
Stationary engine disbursements	269	4	7			
Coach disbursements	6,709	7	11			
Waggon ditto	979	19	8			
Compensation (carrying department)	786	8	2			
Police establishment	1,490	14	1			
Law disbursements	98	9	10			
Bad debts	175	13	6			
				£49,025	18	5

	£	s.	d.
Net profit from 1st July to 31st December, 1831	£40,783	3	7
Dividend per share of £100	4	10	0
Net profit on Sunday travelling per share of £100	0	7	8

HALF-YEAR ENDING 30TH JUNE, 1832.

	Tons.
Merchandise between Liverpool and Manchester	54,174
Traffic to and from different parts of the road	3,707
Between Liverpool and the Bolton junction	14,720
Coals from different parts of the road brought by the Company's engines	22,045
Coals brought by the Bolton engines	7,411

Number of passengers booked at the Company's offices	174,122	
Number of trips of 30 miles performed by locomotive engines with passengers	2,636	
Ditto with merchandise	2,248	
Ditto with coals	234	

Receipts.

Coaching department	£40,044 14 7	
General merchandise department	32,477 14 0	
Coal ditto	2,184 7 6	
		£74,706 16 1

Expenses.

Bad debt account	394 5 7
Coach disbursem[ts]. Guards' and porters' wages, £1,104 4 6.—Parcel carts and drivers' wages, £254 10 5.—Omnibuses and duty, £1,082 0 7.—Repairs and materials, £1,777 9 4.—Gas, oil, tallow, &c., £228 14 6.—Stationery and sundry disbursements, £441 1 7.	4,888 0 11
Carrying disbursem[ts]. Salaries, £1,749 5 10.—Porters' wages, £3,862 0 8.—Brakesmen's wages, £461 5 9.—Oil, tallow, cordage, &c., £461 12 6.—Carting, £808 16 5.—Repairs to jiggers, trucks, &c., £163 14 11.—Stationery and sundry expenses, £503 10 8.	8,010 6 9
Coal ditto	26 8 10
Cartage (Manchester)	1,420 4 9
Charge for direction	308 14 0
Compensation (coaching)	101 10 9
Compensation (carrying)	288 10 3
Coach office establishment (Salaries, £573 13 1.—Rent and taxes, £106 10 0.)	680 3 1
Engineering department	520 9 0
Interest	5,966 14 11
Locomotive power. Fuel and watering, £2,957 8 0.—Oil, tallow, hemp, &c., £507 3 1.—Repairs and materials, £5,947 6 5.—Enginemen's wages, £1,170 18 8.	10,582 16 2
Maintenance of way (wages, £3,929 8 0.—Blocks, sleepers, chairs, &c., £2,668 12 3.—Ballast, £733 0 3)	7,331 0 6
Office establishment (Salaries, £652 8 6.—Rent and taxes, £77 9 2.—Stationery, &c., £81 10 5)	811 8 1
Police and gatekeepers	1,356 9 11
Petty disbursements	75 1 0
Rent	1,840 1 10

Stationary engine and tunnel disbursements, new tunnel rope, £330 10 8.—Coal, £265 7 0.—Wages, £290 9 9.—Repairs, oil, tallow, hemp, &c., £165 8 9	£1,051 16 2	
Taxes and rates	1,109 14 9	
Waggon disbursem^ts. { Smiths' and joiners' wages, £586 6 7.—Iron, timber, &c., £265 0 9.—Canvass, paint, &c., for sheets, £155 10 10 . . . . }	1,006 18 2	
	47,770 15 5	
Deduct credits	1,112 4 1	
		£46,658 11 4
Net profits for six months		£28,048 4 9
Dividend per share of £100		4 0 0
Net profit on Sunday travelling per share of £100 . .		0 4 8

HALF-YEAR ENDING 31ST DECEMBER, 1832.

		Tons.
Merchandise between Liverpool and Manchester		61,995
Ditto to different parts of the road, including the Warrington and Wigan trade, ...		6,011
Ditto between Liverpool and Bolton		18,836
Coals from various parts of the road to Liverpool or Manchester		39,940
Number of passengers booked in the Company's offices	182,823	
Number of trips of 30 miles performed by the locomotive engines with passengers	3,363	
Do. with goods	1,679	
Do. with coals	211	

Receipts.

Coaching department	£43,120 6 11	
General merchandise	34,977 12 7	
Coal department	2,804 3 4	
		£80,902 2 10

Expenses.

Bad debt account	£81 6 0
Coach disbursem^ts. { Guards' and porters' wages, £1,173 19 6.—Parcel carts and drivers' wages, £375 14 4.—Materials for repairs, £464 1 9.—Men's wages, repairing, £613 18 1.—Gas, oil, tallow, &c., £232 11 7.—Duty on passengers, £985 19 1.—Stationery and petty expenses, £414 19 7. . . . . }	4,261 3 11

Carrying disbursem[ts].	Salaries, £1,822 13 2.—Porters', &c., wages, £3,925 7 4.—Gas, oil, tallow, cordage, &c., £296 11 7.—Repairs to jiggers, trucks, stations, &c., £398 3 11.—Stationery and petty expenses, £540 13 5	6,983	9	5		
Coal ditto		27	2	10		
Cartage (Manchester)		2,744	18	7		
Charge for direction		295	1	0		
Compensation (coaching)		209	15	11		
Ditto (carrying)		150	19	11		
Coach office establishment (Salaries, £556 3 10.—Rent and taxes, £75 15 2)		631	19	0		
Engineering department		450	0	0		
Interest		4,555	15	7		
Locomotive power.	Fuel and watering, £3,848 10 8.—Oil, tallow, hemp, &c., £661 1 9.—Materials for repairs, £3,723 9 7.—Men's wages, repairing, £3,352 16 2.—Engine and firemen's wages, £1,060 11 6.	12,646	9	8		
Law disbursements		118	3	8		
Maintenance of way (wages, £3,675 16 5.—Blocks, sleepers, chairs, &c., £2,355 17 1.—Ballast, &c., £846 10 9)		6,878	4	3		
Petty disbursements		66	2	0		
Rent		1,246	5	0		
Stationary engine and tunnel disbursements, (Coal, £209 15 3.—Engine and brakesmen's wages, £316 7 5.—Repairs, gas, oil, tallow, &c., £326 14 7)		852	17	3		
Taxes and rates		3,483	18	2		
Waggon disbursem[ts].	Smiths' and joiners' wages, £583 0 5.—Iron, timber, &c., £350 12 10.—Canvass, paint, &c., for sheets, £31 0 0	964	13	3		
Office establishment (Salaries, £623 18 0.—Rent, £85 0 0.—Stationery, £18 9 0)		727	7	0		
Police ditto		902	16	5		
					£48,278	8 10

Net profit for six months	£32,623	14	0
Dividend per share of £100	4	4	0
Net profit on Sunday travelling per share of £100 . .	0	4	0

HALF-YEAR ENDING 30TH JUNE, 1833.

	Tons.
Merchandise between Liverpool and Manchester	68,284
Ditto to different parts of the line, including Warrington and Wigan	8,712
Ditto between Liverpool, Manchester, and Bolton .	19,461
Coals from various parts, to Liverpool and Manchester . .	41,375

Total number of passengers booked in the Co.'s offices	171,421
Number of trips of 30 miles performed by the locomotive engines with passengers	3,262
Ditto with merchandise	2,244

Receipts.

Coaching department	£44,130	17	2	
Merchandise ditto	39,301	17	3	
Coal ditto	2,638	15	9	
				£86,071 10 2

Expenses.

Advertising account		£50	8	7
Bad debt account		176	18	6
Coach disbursem[ts].	Guards' and porters' wages, £1,150 4 0.—Parcel carts, horse keep, and drivers' wages, £401 18 6.—Materials for repairs, £383 15 11.—Men's wages, repairing, £758 10 6.—Gas, oil, tallow, cordage, &c., £324 4 0.—Duty on passengers, £2,466 15 4.—Stationery and petty expenses, £236 15 6.—Taxes on offices, stations, &c., £112 18 4	5,835	2	1
Carrying disbursem[ts].	Agents' and clerks' salaries, £1,703 17 6.—Porters' and brakesmen's wages, horse keep, &c., £4,687 9 7.—Gas, oil, tallow, cordage, &c., £648 4 11.—Repairs to jiggers, trucks, stations, &c., £405 13 1.—Stationery and petty expenses, £336 9 0.—Taxes, insurance, &c., on offices and stations, £798 1 8	8,579	15	9
Coal disbursements		120	16	1
Cartage (Manchester)		2,460	16	1
Charge for direction		252	0	0
Compensation (coaching)		38	1	2
Compensation (carrying)		1,033	18	3
Coach office establishment (Agents' and clerks' salaries, £577 19 6.—Rent and taxes, £102 17 1)		680	6	7
Engineering department		441	17	4
Interest		5,367	11	9

Locomotive power.	Coke and carting, £2,795 4 5.—Wages to coke fillers, and watering engines, £338 16 10.—Gas, oil, tallow, hemp, &c., £760 15 2.—Copper and brass tubes, iron, timber, &c., for repairs, £3,290 8 8.—Men's wages, repairing, £4,115 0 8. Enginemen and firemen's wages, £892 4 4.—Out-door repairs to engines, £943 6 8.—Two new engines, "Leeds" and "Firefly," £1,580 0 0	14,715	16	9			
Maintenance of way (wages, £3,648 18 5.—Blocks, sleepers, chairs, &c., £2,052 5 11.—Ballast and draining, £1,013 4 11)		6,714	9	3			
Office establishment (Salaries, £624 19 0.—Rent and taxes, £62 18 6.—Stationery, &c., £56 19 5)		744	16	11			
Police		950	4	7			
Petty disbursements		70	0	0			
Rent		601	15	8			
Repairs to walls and fences		296	4	2			
Stationary engine and tunnel disbursements (Coal, £155 8 1.—Engine and brakesmen's wages, £363 8 10.—Repairs, gas, oil, tallow, &c., £340 15 11)		859	12	10			
Tax and rate		1,891	0	7			
Waggon disbursements (Smiths' and joiners' wages, £598 3 1.—Iron, timber, &c., £320 1 4.—Cordage, paint, &c., for sheets, £82 7 3)		1,000	11	8			
Cartage (Liverpool)		18	4	6			
					£52,900	9	1

Net profit for six months	£33,171	1	1
Dividend per share of £100	4	4	0
Net profit on Sunday travelling per share of £100 . .	0	3	6

HALF-YEAR ENDING 31ST DECEMBER, 1833.

	Tons.
Merchandise between Liverpool and Manchester	69,806
Ditto to and from different parts of the line, including Warrington and Wigan	9,733
Ditto between Liverpool, Manchester, and Bolton .	18,708
Coal from various parts to Liverpool and Manchester . .	40,134

Total number of passengers booked at the Co.'s offices	215,071
Number of trips of 30 miles performed by the locomotive engines with passengers	3,253
Do. with merchandise	2,587

Receipts.

Coaching department	£54,685 6 11		
Merchandise ditto	39,957 16 8		
Coal ditto	2,591 6 6		
		£97,234 10 1	

Expenses.

Advertising account		6 10 0
Bad debt account		374 10 1
Coach disbursem^ts.	Guards' and porters' wages, £1,168 4 6.—Parcel carts, horse keep, and drivers' wages, £361 1 7.—Materials for repairs, £689 12 6.—Men's wages, repairing, £1,041 1 3.—Gas, oil, tallow, cordage, &c., £196 4 11.—Duty on passengers, £3,224 11 11.—Stationery and petty expenses, £277 4 5.—Taxes on offices, stations, &c., £116 0 8.—Guards' clothes, £64 15 0.	7,138 16 9
Carrying disbursem^ts.	Agents' and clerks' salaries, £1,728 16 9.—Porters' and brakesmen's wages, horse keep, &c., £5,006 6 10.—Gas, oil, tallow, cordage, &c., £529 17 0.—Repairs to jiggers, trucks, stations, &c., £366 9 11.—Stationery and petty expenses, £429 5 1.—Taxes and insurance on offices, &c., £456 17 7.—Sacks for grain, £110 3 10	8,627 17 0
Coal disbursements		82 0 9
Cartage (Manchester)		3,173 18 0
Charge for direction		312 18 0
Compensation (coaching)		142 4 8
Compensation (carrying)		223 10 11
Coach office establishment (Agents' and clerks' salaries, £602 6 8.—Rent, £30)		632 6 8
Engineering department		319 3 4
Interest		5,140 6 4
Locomotive power.	Coke and carting, £3,197 4 4.—Wages to coke fillers and waterers, £348 8 5.—Gas, oil, tallow, hemp, cordage, &c., £865 14 9.—Brass and copper, iron, timber, &c., for repairs, £3,755 3 7.—Men's wages, repairing, £4,401 4 10.—Engine and firemen's wages, £784 8 5.—Out-door repairs to engines, £613 3 9	13,965 8 1

Maintenance of way. { Wages to plate-layers, joiners, &c., £2,937 19 2.—Stone, blocks, sleepers, keys, chairs, &c., £2,411 2 4.—Ballasting and draining, £925 16 11.—New rails, £150 16 3 . . . . }	6,425 14 8		
Office establishment (Salaries, £607 2 0.—Rent and taxes, £75 14 3.—Stationery and printing, £22 7 8.—Stamps, £17 2 3)	722 6 2		
Police	1,022 7 6		
Petty disbursements	61 19 6		
Rent	603 10 8		
Repairs to walls and fences	665 3 4		
Stationary engine and tunnel disbursements, (Coal, £302 6 5.—Engine and brakesmen's wages, £319 11 2.—Repairs, gas, oil, tallow, &c., £419 15 5.—New rope for tunnel, £266 3 6) .	1,307 16 6		
Tax and rate	3,409 11 0		
Waggon disbursem[ts]. { Smiths' and joiners' wages, £718 19 7.—Iron, timber, castings, &c., £700 9 1.—Cordage, paint, &c., £28 5 2.—Canvass for sheets, £163 6 5 . . . . }	1,611 0 3		
Cartage (Liverpool)	80 17 10		
Law disbursements	300 3 9		
		£56,350 1 9	

Net profit for six months	£40,884 8 4
Dividend per share of £100	4 10 0
Net profit on Sunday travelling per share of £100 . . .	0 5 3
Reserved fund formed in the six months	4,088 8 10

HALF-YEAR ENDING 30TH JUNE, 1834.

		Tons.
Merchandise between Liverpool and Manchester		69,522
To and from different parts of the road, including Warrington and Wigan		15,201
Between Liverpool, Manchester, and Bolton		19,633
Coal to Liverpool and Manchester		46,039
Number of passengers booked at the Company's offices	200,676	
Number of trips of 30 miles performed by the locomotive engines with passengers	3,317	
Ditto with merchandise	2,499	

Receipts.

Coaching department	£50,770 16 11	
Merchandise ditto	41,087 19 5	
Coal ditto	2,925 15 11	
		£94,784 12 3

Expenses.

Advertising account	£16 15 0
Bad debt ditto	75 12 3

		£	s.	d.
Coach disbursemts.	Guards' and porters' wages, £1,167 11 10.—Parcel carts, horse keep, and drivers' wages, £359 13 0.—Materials for repairs, £1,007 9 7.—Men's wages, repairing, £1,221 15 5.—Gas, oil, tallow, cordage, &c., £358 15 6.—Duty on passengers, £3,008 1 11.—Stationery and petty expenses, £165 2 5.—Taxes, insurance, &c., on offices and stations, £65 8 11 . . .	7,353	18	7
Carrying disbursemts.	Agents' and clerks' salaries, £1,740 14 2.—Porters' and brakesmen's wages, horse keep, &c., £5,397 8 5.—Gas, oil, tallow, cordage, &c., £708 17 4.—Repairs to jiggers, trucks, stations, &c., £716 2 8.—Stationery and petty expenses, £290 3 2.—Taxes, insurance, &c., on offices and stations, £469 6 2	9,322	11	11
Coal disbursements		45	1	0
Cartage (Manchester)		2,988	6	2
Charge for direction		289	16	0
Compensation (coaching)		26	3	10
Compensation (carrying)		645	6	0
Coach office establishment (Agents' and clerks' salaries, £615 1 11.—Rent and taxes, £63 1 1) .		678	3	0
Engineering department		352	10	0
Interest		5,546	4	0
Locomotive power.	Coke and carting, £2,882 11 4.—Wages to coke fillers, and watering engines, £386 19 5.—Gas, oil, tallow, hemp, &c., £881 18 4.—Copper and brass tubes, iron, timber, &c., for repairs, £4,140 19 6.—Men's wages for repairing, £5,432 8 8.—Enginemen and firemen's wages, £836 14 3.—A new engine, £700.—Lathe engine, boiler and fixing for repairing sheds and watering stations, £380 6 4	15,641	17	10
Law disbursements		100	0	0
Maintenance of way.	Wages and small materials, £4,221 2 5.—Stone, blocks, sleepers, &c., £1,482 18 7.—New rails and chairs, points, crossings, &c., £3,153 14 5.—Ballast and leading, £493 2 0 .	9,350	17	5
Office establishment (Salaries, £818 14 4.—Rent and taxes, £58 8 0)		877	2	4
Police		1,016	18	1
Petty disbursements		60	0	0
Rent		363	11	11

Statio gine and tunnel disbursements, (Coal, £32 1.—Engine and brakesmen's wages, £38 .—Repairs, gas, oil, tallow, &c., £273 11	986	10	2			
Tax a e	1,778	16	10			
Wa disbu . { Smiths' and joiners' wages, £773 3 8.—Iron, timber, &c., £728 12 4.—Cordage, paint, &c., £109 19 2.—Canvass for sheets, £240 . . . . }	1,851	15	2			
Repai walls and fences	644	0	11			
Carta iverpool)	80	17	6			
				£60,092	15	11
Net profit for six months				£34,691	16	4
Dividend per share of £100				4	10	0
Net profit on Sunday travelling per share of £100 . . .				0	5	2

THE END.

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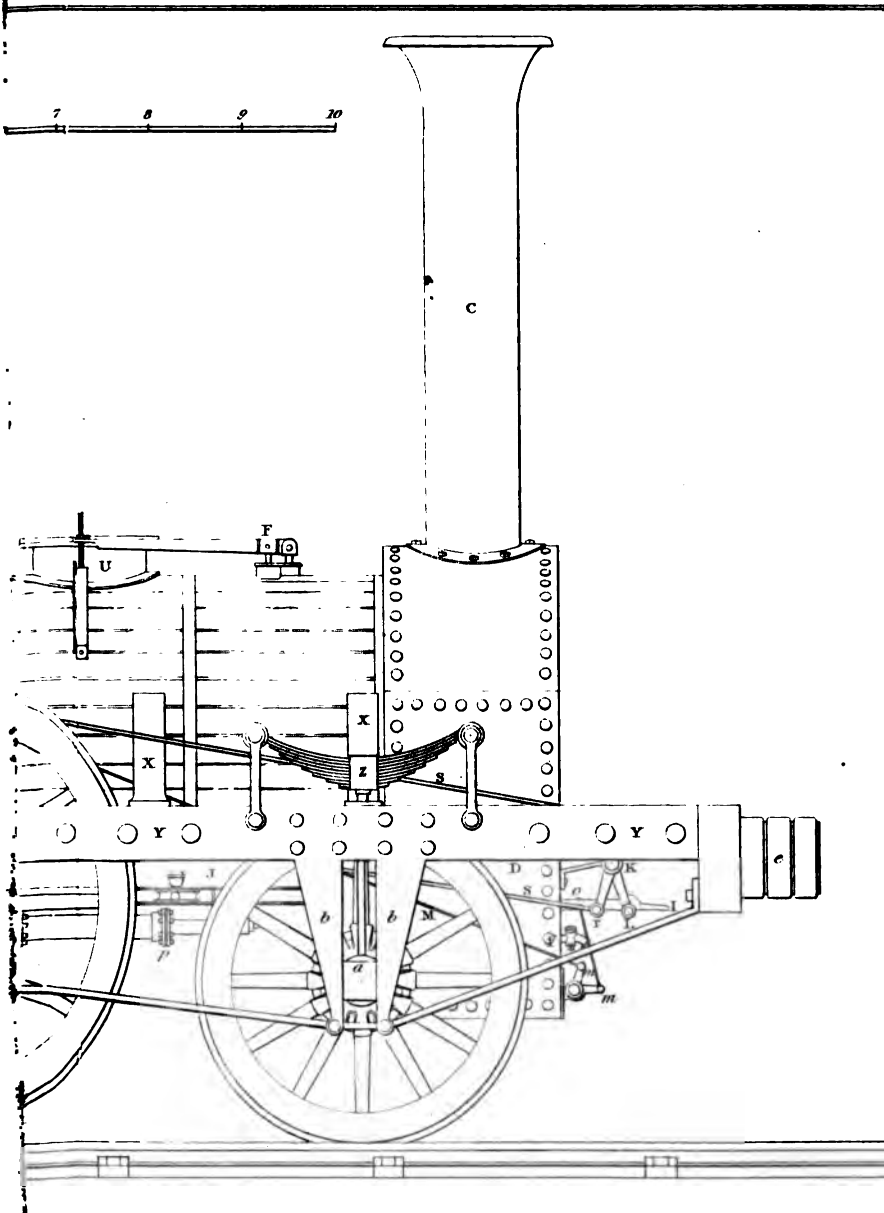
Pl.



S. Porter

Pl. 3

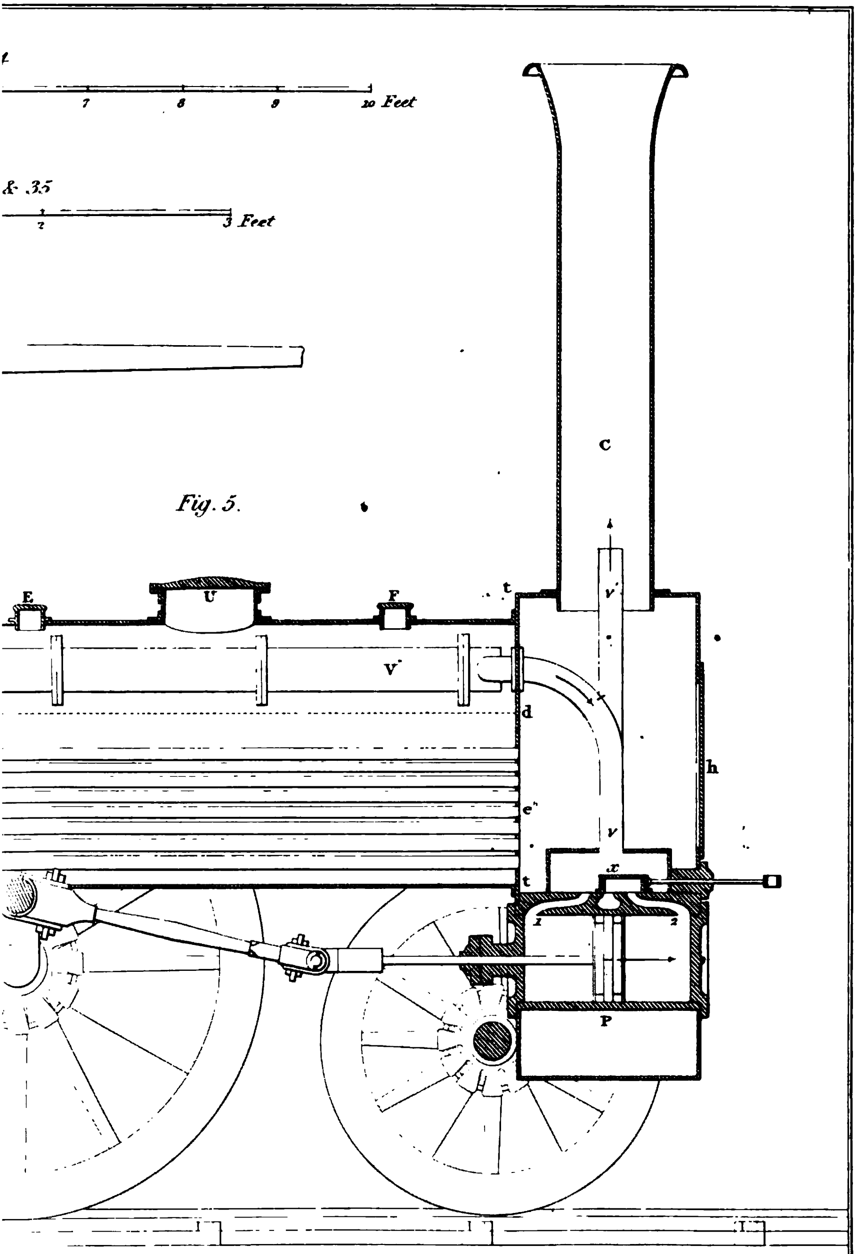


Fig. 5.

S. Porter sc.

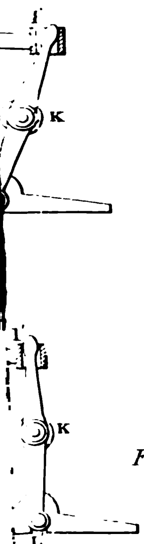


Fig. 8.

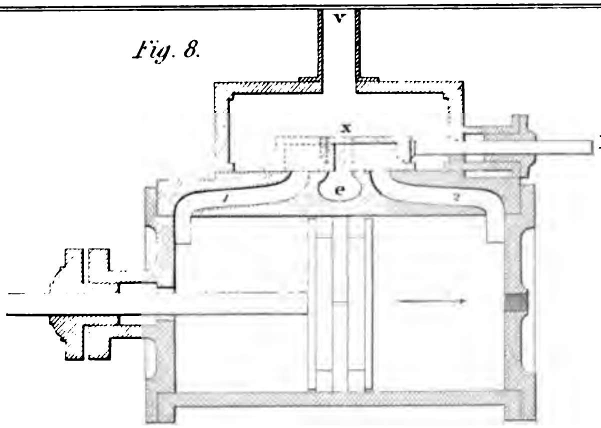


Fig. 25.

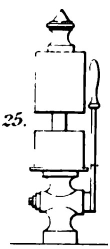
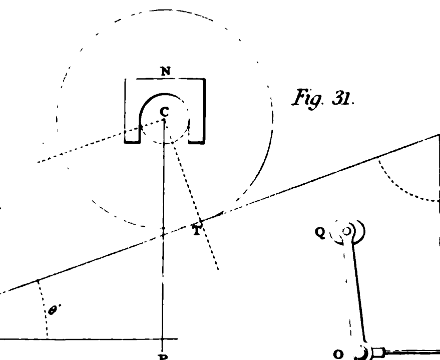


Fig. 31.



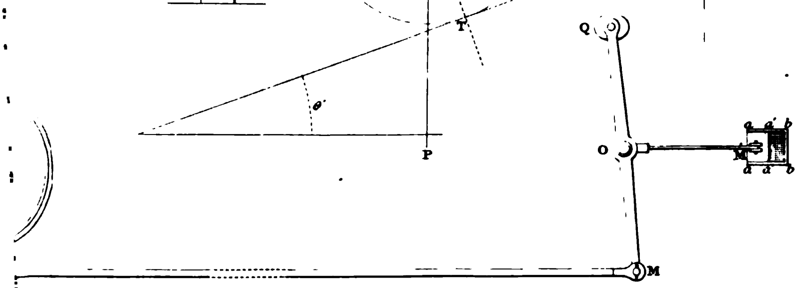
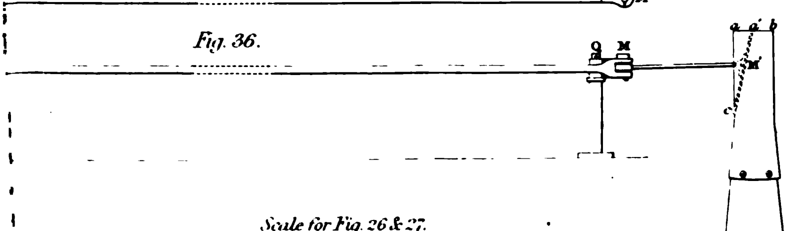
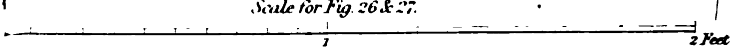


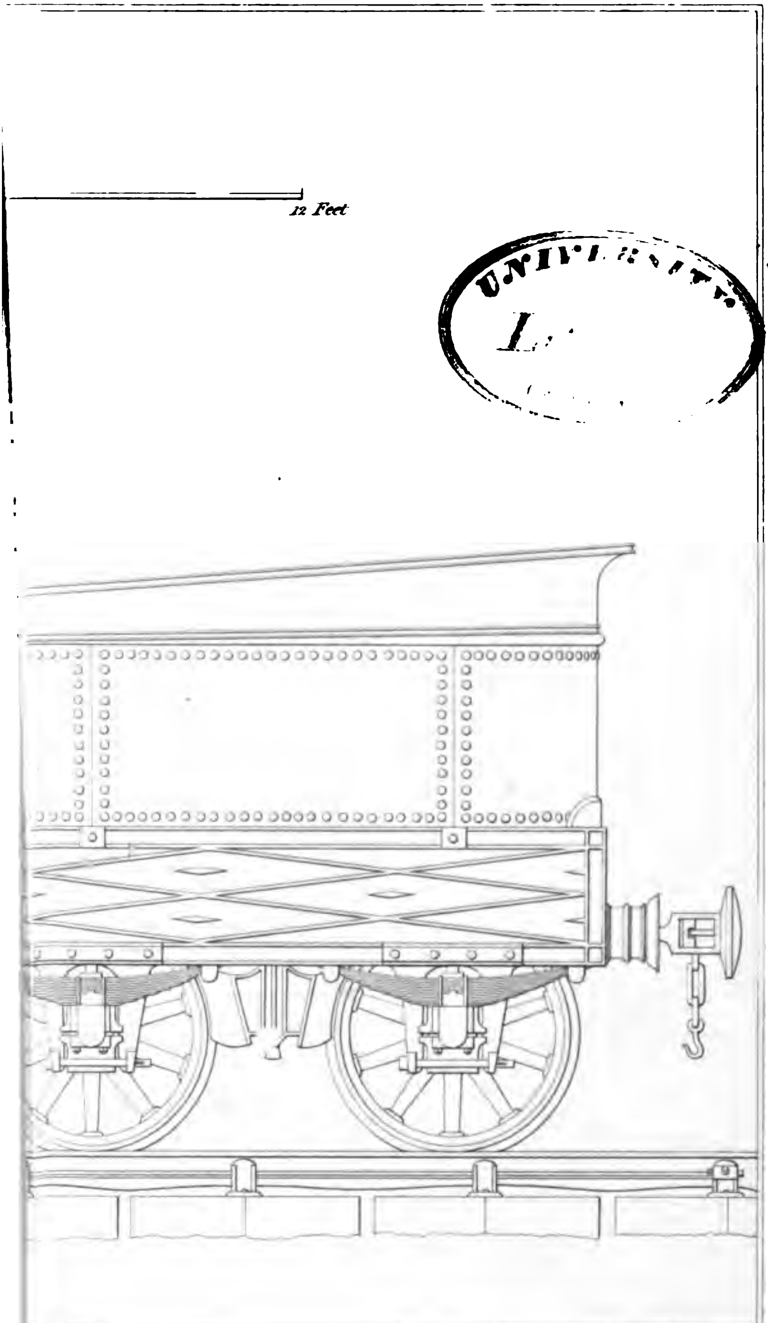
Fig. 36.



Scale for Fig. 26 & 27.



S. Porter sc.



F. Mansell sc.

Fig. 23.

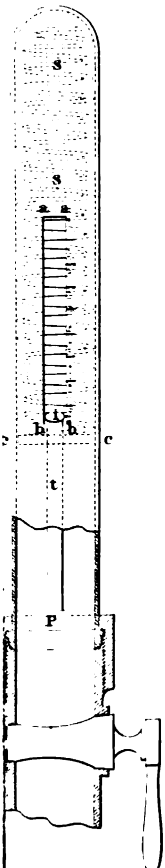


Fig. 24.

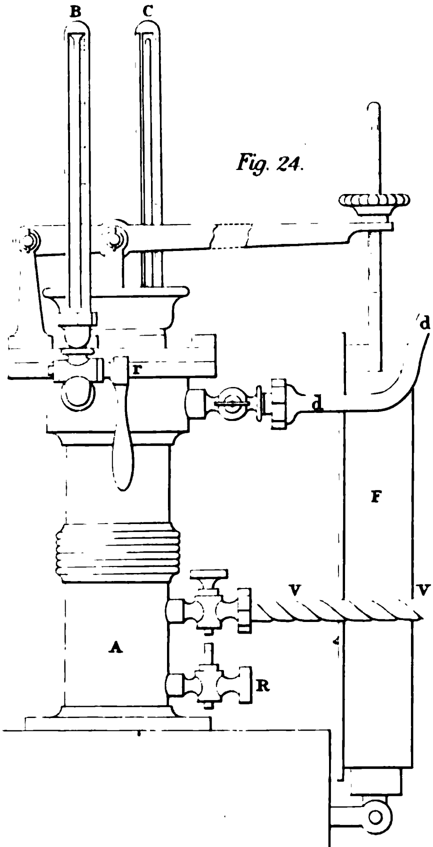


Fig. 18.

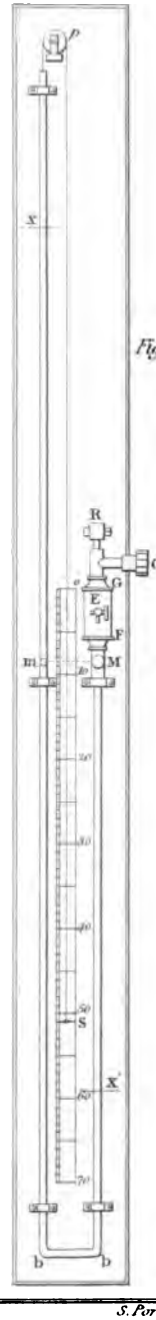
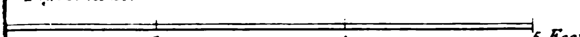
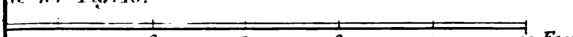


Fig. 24.

r Fig. 15. & 16.



le for Fig. 18.



S. Porter sc